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A Framework for Interoperability on the United States Electric Grid Infrastructure

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A FRAMEWORK FOR INTEROPERABILITY ON THE UNITED STATES ELECTRIC GRID INFRASTRUCTURE

by

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ABSTRACT

Historically, the United States (US) electric grid has been a stable one-way power delivery infrastructure that supplies centrally-generated electricity to its predictably consuming demand. However, the US electric grid is now undergoing a huge transformation from a simple and static system to a complex and dynamic network, which is starting to interconnect intermittent distributed energy resources (DERs), portable electric vehicles (EVs), and load-altering home automation devices, that create bidirectional power flow or stochastic load behavior. In order for this grid of the future to effectively embrace the high penetration of these disruptive and fast-responding digital technologies without compromising its safety, reliability, and affordability, plug-and-play interoperability within the field area network must be enabled between operational technology (OT), information technology (IT), and telecommunication assets in order to seamlessly and securely integrate into the electric utility's operations and planning systems in a modular, flexible, and scalable fashion.

This research proposes a potential approach to simplifying the translation and contextualization of operational data on the electric grid without being routed to the utility datacenter for a control decision. This methodology integrates modern software technology from other industries, along with utility industry-standard semantic models, to overcome information siloes and enable interoperability. By leveraging industrial engineering tools, a framework is also developed to help devise a reference architecture and use-case application process that is applied and validated at a US electric utility.

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LIST OF ACRONYMS/ABBREVIATIONS

3G	3rd Generation of mobile telecommunications technology
4G	4th Generation of mobile telecommunications technology
6LoWPAN	IPv6 over Low power Wireless Personal Area Networks
AEP	American Electric Power
ADR	Automated Demand Response
AEC	Architecture, Engineering, and Construction
AMI	Advanced Metering Infrastructure
AMQP	Advanced Message Queue Protocol
API	Application Programming Interface
ARRA	American Recovery & Reinvestment Act of 2009
CAIDI	Customer Average Interruptions Durations Index
CAIFI	Customer Average Interruptions Frequency Index
CHP	Combined Heat and Power
CIM	Common Information Model
CIS	Customer Information System
CORBA	Common Object Request Broker Architecture
COTS	Commercial Off-the-Shelf
CPU	Central Processing Unit
DA	Distribution Automation
DAP	Data Aggregation Point

DCPS	Data-Centric Publish-Subscribe
DDS	Data Distributed Service for Real-Time Systems
DDSI	DDS Interoperability wire protocol specification
DER	Distributed Energy Resource
DG	Distributed Generation
DHCP	Dynamic Host Configuration Protocol
DIP	Distributed Intelligence Platform
DMS	Distribution Management System
DNP	Distributed Network Protocol
DNS	Domain Name System
DOE	Department of Energy
DoD	Department of Defense
DRE	Distributed, Real-time, and Embedded systems
DTE	Detroit Edison
EA	Enterprise Architect by Sparx Systems
EAI	Enterprise Application Integration
EAM	Enterprise Asset Management
ECC	Energy Control Center
EIF	European Interoperability Framework
EMS	Energy Management System
EPRI	Electric Power Research Institute
ERP	Enterprise Resource Planning

ESB	Enterprise Service Bus
ESM	Enterprise Semantic Model
FAN	Field Area Network
FAN Gw	Field Area Network Gateway
FMB	Field Message Bus
FDIR	Fault Detection Isolation & Restoration
FLISR	Fault Location Isolation Sectionalization & Restoration
GIS	Geographic Information System
GPS	Global Positioning System
HIEI	Healthcare Information Exchange and Interoperability
HMI	Human Machine Interface
HTTP	Hypertext Transfer Protocol
HVAC	Heating, Ventilation, and Cooling
HW	Hardware
ICT	Information and Communication Technology
IDL	Interface Description Language
IEC	International Electrotechnical Commission
IEC 61850	IEC standard data model for substation assets
IEC 61968	IEC standard data model for distribution and metering assets
IEC 61970	IEC standard data model for transmission assets
IEC 62325	IEC standard data model for energy markets
IEEE	Institute of Electrical and Electronic Engineers

IED	Intelligent Electronic Device
IOS	Interorganizational Systems
IOU	Investor-Owned Utility
IP	Internet Protocol
IS	Information Systems
ISM	Industrial, Scientific and Medical radio band
ISSA	International Social Security Association
IT	Information Technology
IOA	Interoperable Open Architecture
IoT	Internet of Things
JMS	Java Message Service
kW	Kilowatt
LAN	Local Area Network
LCIM	Levels of Conceptual Interoperability Model
LED	Light-Emitting Diodes
LTE	Long Term Evolution
M2M	Machine-to-Machine
MAIFI	Momentary Average Interruptions Frequency Index
MBSE	Model Based System Engineering
MD3i	Model Driven Information, Integration and Intelligence
MDA	Model Driven Architecture
MDG	Model Driven Generation technology

MDM	Meter Data Management
MG	Microgrid
MGC	Microgrid Controller
MIT	Massachusetts Institute of Technology
MOC	Matrix of Change
MOM	Message-Oriented Middleware
MQTT	Message Queue Telemetry Transport
MW	Megawatt
NCOW	Network-Centric Operations and Warfare
NIST	National Institute of Standards & Technology
NMS	Network Management System
NOx	Nitrogen Oxides
O&M	Operations & Maintenance
OASIS	Organization for Advancement of Structured Information Standards
OEM	Original Equipment Manufacturer
OMG	Object Management Group
OMS	Outage Management System
OS	Operating System
OSI	Open Systems Interconnection
OT	Operational Technology
OWL	Web Ontology Language
PAN	Personal Area Network

PIM	Platform Independent Model
PLC (1)	Programmable Logic Controller
PLC (2)	Power Line Carrier
PMU	Phasor Measurement Unit or synchrophasor
Pub/Sub	Publish-Subscribe
QoS	Quality of Service
RDF	Resource Description Framework
RTI	Real-time Innovations
RTPS	Real-Time Publish-Subscribe
PV	Photovoltaic
RF	Radio Frequency
RTU	Remote Terminal Unit
SAIDI	Sum of All Interruptions Durations Index
SAIFI	Sum of All Interruptions Frequency Index
SCADA	Supervisory Control and Data Acquisition
SDK	Software Development Kit
SDN	Software Defined Networking
SME	Subject Matter Expert
SNMP	Simple Network Management Protocol
SOA	Service Oriented Architecture
SoS	System of Systems
SOx	Sulfur Oxides

SSH	Secure Shell
SSL	Secure Socket Layer
SW	Software
T&D	Transmission & Distribution
TCP	Transmission Control Protocol
TC57	Technical Committee 57
TLS	Transport Layer Protocol
UCAIug	Utility Communications Architecture International Users Group
UDP	User Datagram Protocol
UML	Unified Modeling Language
UPS	Uninterruptable Power Supply
UUID	Universal User Identification
VM	Virtual Machine
Var	Volt-ampere reactive
VVO	Volt-Var Optimization
WAN	Wide Area Network
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
XML	Extensible Markup Language
XSD	XML Schema Definition

CHAPTER 1: INTRODUCTION

Unlike the first century of its existence, the United States (US) electric power grid infrastructure has been experiencing a lot of change during the past decade or two. This transformation has not only impacted the method energy producers supply electricity, but also the manner it is consumed. As a result, there has been a rapid evolution in the way that US utilities or energy producers have embraced and implemented information technology (IT) and telecommunications systems in effort to more effectively manage these newer and more complex operational behavioral patterns without compromising safety, reliability, and affordability.

In addition, many of the emerging technologies, that affect the supply and demand of electricity, are introducing digital elements to the power system. These new digital technologies on the grid, that are intermittent by nature, are not easily aligned or synchronized with the traditional grid infrastructure, which typically delivers power from a central plant supplied by rotating mass generation sources. When there was a low penetration of asynchronous operational functions on the conventional one-way power flow electric grid system, there was not an urgent need in the US utility industry for field interoperability among grid assets outside of the back-office control centers. However, as the future state of the grid evolves to a two-way power flow system with a diverse mix of distributed generation (DG) sources and dynamic loads, the need for enabling interoperability on the existing aged grid infrastructure will become a higher priority for the US utilities that are embracing the grid of the future in an sustainable way.

This chapter begins by providing backgrounds of the various states of the US electric grid infrastructure, the current technologies in the utility industry, and the new innovative technology trends in other industries that can be potentially leveraged to enable interoperability on the electric grid. This chapter then sequentially identifies the problem statement, research question, and research contribution, which includes a potential solution alternative. Lastly, an overall outline of the dissertation is revealed.

1.1 Background

This section provides the background information essential for understanding the fundamental terminologies and key types of technologies within the US electric power system domain and the emerging technology trends in other industries that are relevant to this research. The first three subsections describe the traditional, current, and future states of the US electric grid. The next subsection covers the underlying technology trends presently witnessed in the US utility sector. Lastly, the final subsection introduces some new innovative technology trends in other industries that have the potential to enable interoperability in a digital ecosystem.

1.1.1 Traditional State of the Electric Grid

The best way to describe the traditional state of the electric grid in the US is that of a centralized power delivery system, epitomizing a pipe, otherwise known as transmission and distribution lines, that connects and delivers electricity one-way from the supply, provided by source(s) of central generation, to the demand, consumed by load on the customer premise. Figure 1-1, adapted from the Electric Power Research Institute [EPRI] (2014), shows how this traditionally simple and static path from a historically handful of large power generation plants is fed to a relatively sizable amount of predictable customers that typically do not produce or store energy.

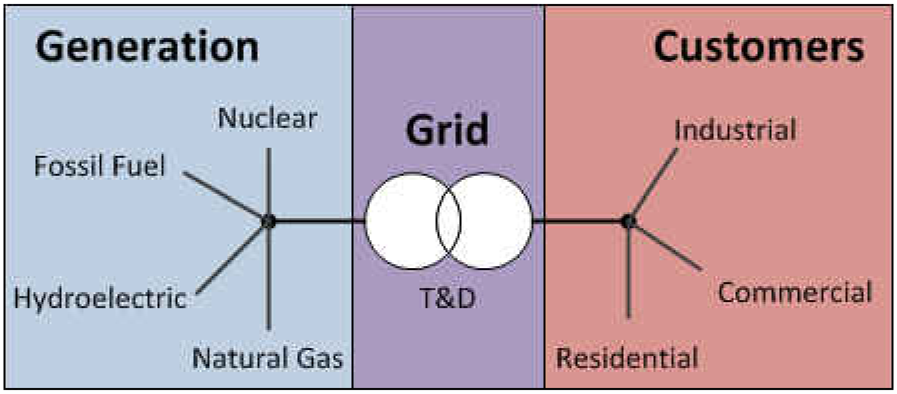


Figure 1-1: Traditional State of the US Electric Grid (adapted from EPRI, 2014)

In the traditional grid, there were very few generators on the customer side, which were mainly used for back-up power supply during an outage. Moreover, the life expectancy of the power grid assets was typically around 30-50 years since they were mainly comprised of ruggedized analog electromechanical equipment. For many years, this system topology was effective for delivering safe, reliable, and affordable energy.

1.1.2 Current State of the Electric Grid

Similar to the traditional topology, the current state of today's US electric grid, as adapted from Brooks (2014) in Figure 1-2, is also characterized as a safe, reliable, and affordable one-way power delivery pipe between the generation and customer sides.

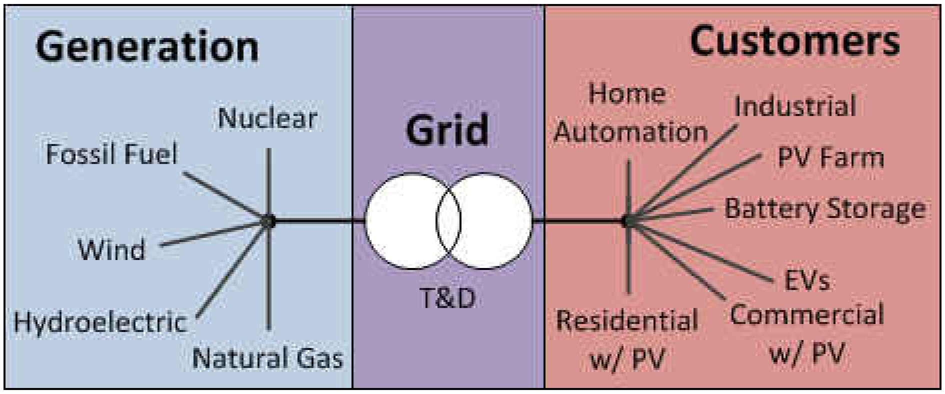


Figure 1-2: Current State of the US Electric Grid (adapted from Brooks, 2014)

However, since there have been external efforts to reduce the environmental impact of carbon emissions from fossil fuels, there has been a large increase, on both the supply and demand sides of the electric grid, in the number of interconnections of inverter-based distributed energy resources (DERs), such as solar photovoltaic (PV), wind turbines, battery storage, electric vehicles, and combined heat and power (CHP) with natural gas. Likewise, the grid infrastructure has also been adding a lot of new digital telecommunications devices and IT systems in effort to connect better with the customer side for the enablement of smart metering capabilities and automated demand response (ADR) programs that regulate the in-premise motor-based appliances, such as the heating, ventilation, air, and cooling (HVAC) equipment and pool pumps.

Unlike the other industries where digital technologies have less than a 5 year shelf life, today's US utility industry has embraced grid automation devices or systems that were designed in the 1990's and 2000's with an expected shelf life of 10-20 years. Additionally, since the technology capabilities for the digital telecommunications, computing hardware, and software applications were still at their infancy and the customer load demand was predictability stable during this timeframe, the response times for the legacy automation systems were not fast and high latencies in the collection and processing of the actionable information were tolerated by the US utility operations and management stakeholders. Moreover, as these systems were being selected and deployed, many of them were implemented in an open-loop and hub-and-spoke topology, which consisted of many single-purpose, proprietary solutions that are not interoperable and do not integrate easily with other vendors' products or systems. Furthermore, in order to successfully implement a complete operational function in a timely and risk-adverse fashion, one vendor or system integrator was typically chosen to execute and deliver the end-to-end system requirements using proprietary components that fundamentally siloed the information within their selected combination of hardware, software, and telecommunications.

1.1.3 Future State of the Electric Grid

As adapted from EPRI (2014) in Figure 1-3, the future state of the electric grid is a flattened network ecosystem of plug-and-play assets and systems that are able to harmoniously interconnect electrically and seamlessly share information with each other. It is also important to note that while the majority of PV farms are owned by customers today and not by utilities, the future trend is gearing toward seeing a mix of both customer-owned and utility-owned PV assets. This future power system, referred to by EPRI as "the integrated grid," requires interoperability in order to ensure an integrated infrastructure that is safe, reliable, affordable, environmentally friendly, flexible, and resilient.

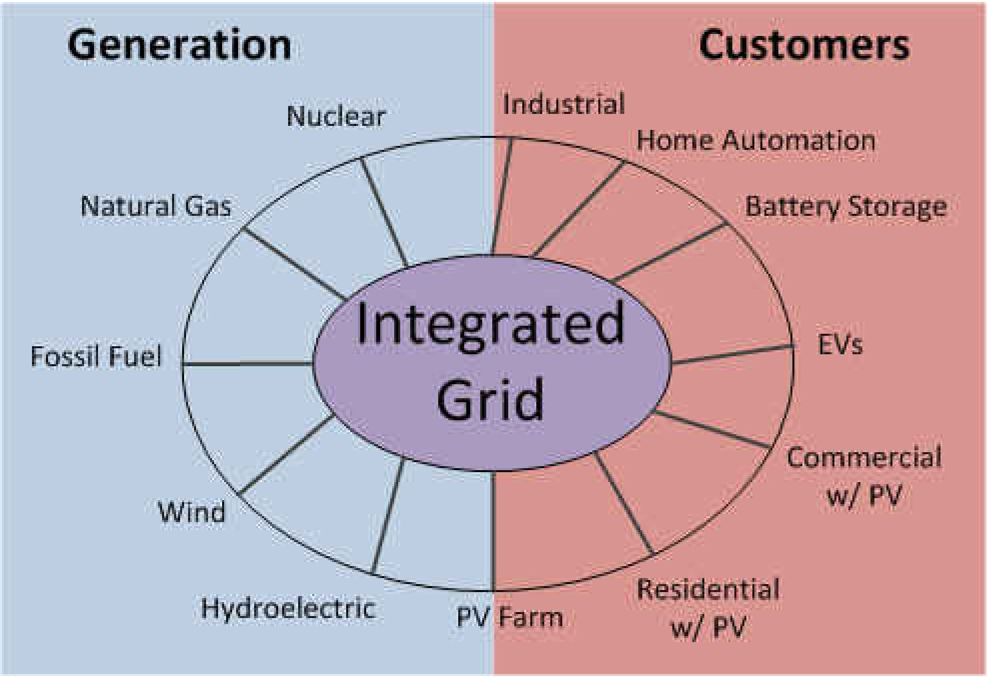


Figure 1-3: Future State of the US Electric Grid (adapted from EPRI, 2014)

Similar to the current state, the future state of the grid is driven by the penetration and adoption of new disruptive technologies, such as DERs and in-premise automation. However, with this future grid infrastructure having a much higher penetration of information-rich digital technologies, the amount and complexity of data being collected and stored by these assets and systems, especially in the utility back-office datacenter, will continue to grow exponentially. Moreover, the maturity of the US telecommunications infrastructure, in both wireless cellular networks and wired broadband, along with the emergence of the open software applications on smartphones and machine-to-machine (M2M) devices, will continue to drive the need for instant access, connectivity, and services via an internet protocol (IP) network. Consequently, it is anticipated that more sensing devices and data points will be added to the future grid and the energy customers will expand their access to home automation devices and software services to monitor and control the energy usage. Furthermore, these innovative technology trends in the external markets will not only change the future operational expectations for managing a bi-directional power flowing electric grid and an ubiquitous heterogeneous telecommunication network at the US utility company, but also change the behavior and volatility of customers and suppliers.

Table 1-1: Comparison of the Current and Future States of the US Electric Grid

Feature	Current State	Future State
Generation Sources	Centralized	Distributed & Centralized
Power Flow	One-way	Bi-directional
Telecom	None or One-way, not real-time	Two-way in near-real-time
Equipment	Analog & Electromechanical	Digital & Automated
Assets	Single-purpose	Multi-function
Technology	Proprietary	Modular, Interchangeable
Systems	Silo-oriented	Integrated, Interoperable
Grid Topology	Static	Dynamic
Analytics	Reactive	Predictive
Maintenance	Time-based	Condition-based
Security	Within Datacenter Firewall	All Devices & Systems
Information	Complex & Big Data Overload	Filtered & Timely
OT/IT	Disconnected	Converged
Utility & Customer	Limited Interaction	Virtual Hand-shake
Load Forecast	Stable	Stochastic

When these new trends are combined with the aging infrastructure that requires a heavy price tag to upgrade or maintain, the US utilities in the future will be faced with the task of affordably and reliably scaling their electric grid infrastructure and back-office systems in a sustainable way to satisfy the new customer expectations and stochastic load behaviors at the premise. As depicted above in Table 1-1, a brief summary of these key anticipated changes in the future state versus the current state are provided and will be discussed in greater detail throughout the subsequent sections and chapters in this thesis (adapted from ABB, 2009).

1.1.4 Technology Trends in the US Electric Utility Industry

During the past decade, the US electric utility industry has been facing external pressure from its customers and policymakers to innovate its electric grid infrastructure due to potential environmental impacts, such as global warming, as well as the numerous catastrophic outages caused by adverse weather conditions, such as hurricanes and blizzards. As a result, efforts to modernize the electric grid were initiated by the US Department of Energy (DOE), which attempted to incentivize domestic utilities to invest in “smart grid” technologies funded by federal grants made available by the American Recovery and Reinvestment Act (ARRA) in 2009 (US DOE, 2012). Though the ARRA grants were successful in attracting utilities to make quick substantial grid investments in a short time frame, it is unclear whether these new smart grid technologies were vetted diligently and positioned the utilities to be better off in the long-run, where the future state of the grid is an interoperable and integrated network of devices and systems. These existing smart grid technologies, which are to be discussed in detail throughout this section, are separated into three different categories and subsections: operational technology (OT), information technology (IT), and telecommunications.

1.1.4.1 Operational Technology

Operational Technology (OT) consists of hardware and software that is responsible for enhancing and facilitating the delivery of electricity on the grid via the monitoring, measuring, and controlling of the assets and processes on the physical power delivery infrastructure. Hardware device examples of OT on the electric grid infrastructure include meters, sensors, programmable logic controllers (PLC), remote terminal units (RTU), intelligent electronic devices (IED), and grid apparatus equipment. Software system examples of OT in the utility sector include back-office industrial control systems, such as Supervisory Control and Data Acquisition (SCADA), Distribution Management System (DMS), Energy Management System (EMS), and Outage Management System (OMS).

The most commonly deployed OT hardware technologies over the past 5 years were smart meters, capacitor banks, voltage regulators, IEDs, intelligent switches (or reclosers), fault detecting sensors, transformer monitors, and inverter-based control systems for solar PV, wind, battery storage, and electric vehicle chargers. By integrating these devices into the grid, situational awareness, security, and reliability were expected to be improved, while enhancing the efficiency of the power distribution network by measuring more accurately. However, since the lion-share of these OT devices available to US utilities, at the time, were designed to meet the extreme outdoor ruggedness and long 10-20 year shelf-life requirements of the traditional electric grid, they lacked the modern telecommunications and computing capabilities that are available in today's commercial off-the-shelf (COTS) consumer and industrial telematics solutions. Also, given the short deadlines proposed by the DOE to make decisions on their ARRA grants participation, many utilities were rushed into selecting and deploying traditional OT vendor hardware solutions, where most were single-purpose proprietary systems that contained obsolete embedded computing and limited telecommunication capabilities.

The most commonly selected OT software systems that utilities deployed during the recent smart grid era were namely the DMS, OMS, and SCADA systems for controlling the protection and control assets on the grid. However, many of these OT software systems were proprietary and optimized for integration with the same vendor equipment or their prescribed Original Equipment Manufacturers (OEM) partner's OT solution. Given that many OT hardware devices deployed on the grid were not all from the same vendor's OT systems implementation, significant integration work is required for translating each OT device protocol to a common language and data model that the centralized OT software system can understand. Moreover, since this translation and contextualization of this OT data takes place in the back-office, the response times for the enterprise OT SCADA systems, such as the DMS or OMS, to collect and process the all field asset information can take 15 minutes or longer for a centralized system-wide control decision. This unanticipated phenomenon is not only a byproduct of the limited wireless bandwidth capabilities, but also due to the reliance on the OT-vendor bundled back-office IT head-end servers necessary for decrypting and translating the field data that is collected and siloed from the OT sensing device.

1.1.4.2 Information Technology

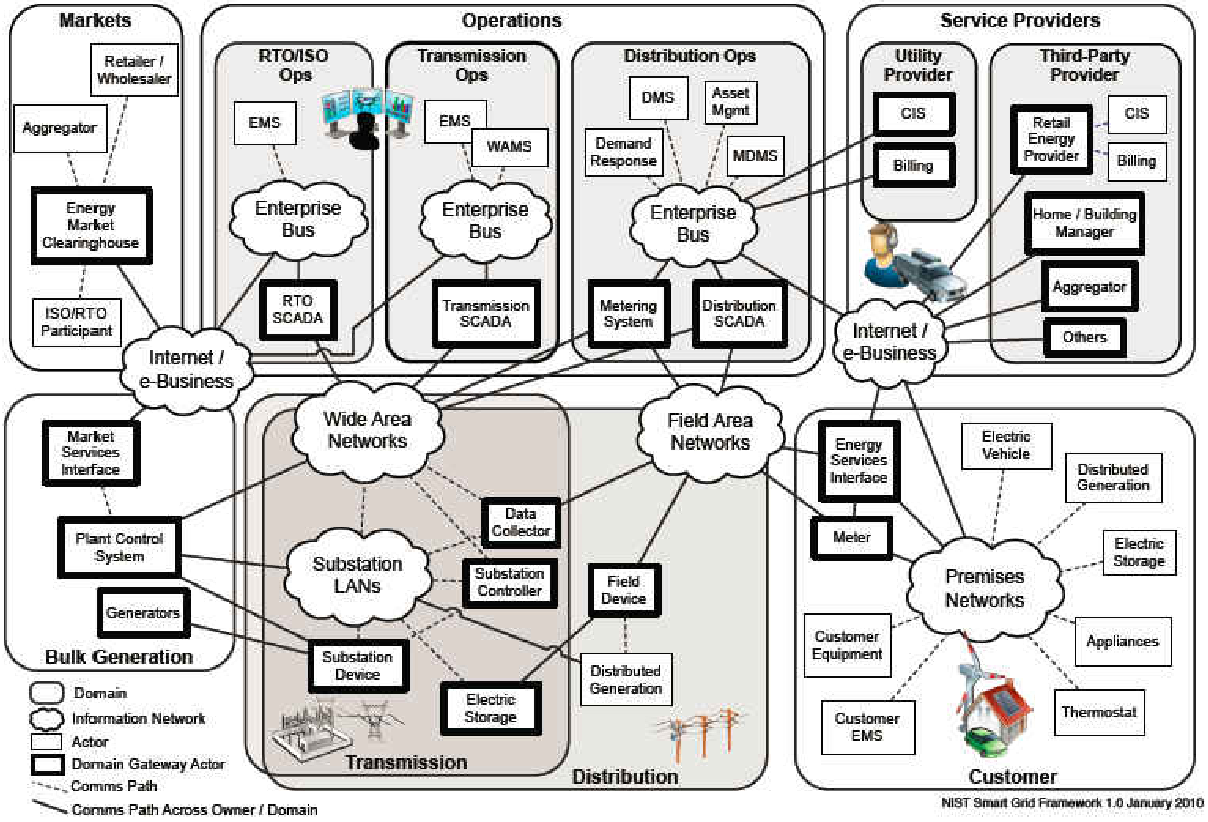
Information Technology (IT) as it relates to the US electric grid comprises of software and services mainly running on servers in the back-office datacenters. This type of software predominantly serves corporate administrative functions, such as billing, customer information systems (CIS), enterprise asset management (EAM), enterprise resource planning (ERP), meter data management (MDM) systems, and network management systems (NMS). Consequently, the customer or asset information collected in these databases are traditionally structured, receive-only data points and not intended to be used for the control and optimization of the grid infrastructure. Given these initial IT system deployments did not have the same requirements of, nor did they expect to interface with, the OT systems, opportunities were created for enterprise IT giants, such as IBM and Oracle, to enter the utility space.

As these smart grid IT system rollouts completed, more and more proprietary systems found their way into the utility back-office datacenter. However, these IT software technologies that were developed to sort and store large quantities of static, structured information in relational databases were not intended to make fast operational decisions, so interfacing with unstructured OT data was not a design goal. As a result, many of the utilities back-office systems today are not optimized for the integration of OT and IT data on the same platform.

One of the recent IT technologies, employed by the US electric utilities to reduce the complexity in the back-office during these recent smart grid deployments, is the enterprise application integration (EAI) service-oriented architecture (SOA), known as the enterprise server bus (ESB). The implementation of the ESB at utilities has shown to be a good step forward since it reduces the number of legacy point-to-point interfaces and also provides a data abstraction layer that simplifies the mapping, translation, routing, interaction, and version control between the various disparate OT and IT systems (Rouse, 2007).

1.1.4.3 Telecommunications

Telecommunications refers to the technologies that physically connect devices and systems to the data communications network as well as the transport medium for information over distances. Though much attention has spent by the utilities to address the OT-IT data integration challenges in the back-office datacenter, the smart grid telecommunications technologies cannot be ignored as it also contributes to the lack of interoperability and higher system latencies. Figure 1-4 illustrated by the National Institute of Standards and Technology [NIST] (2011) shows their smart grid conceptual reference diagram to represent the various OT-IT domains, actors, interfaces, communication paths, and data flows at a utility.



NIST Smart Grid Framework 1.0 January 2010

Figure 1-4: NIST's Smart Grid Conceptual Reference Diagram for the Electric Grid (2011)

Figure 1-5, also illustrated by NIST on the next page, dives deeper inside the typical utility distribution operations field area network (FAN), which includes both the SCADA and Advanced Metering Infrastructure (AMI) systems (2011). However, as shown in Figure 1-5, both of these OT systems on are multiple separate and siloed telecom networks via the Data Aggregation Points (DAP) and FAN gateways (FAN Gw) (2011). As described earlier, a substantial portion of utility-grade OT meters and sensors deployed on the smart grid were developed with telecommunications solutions that did not leverage the innovation and maturity of the mainstream cellular markets.

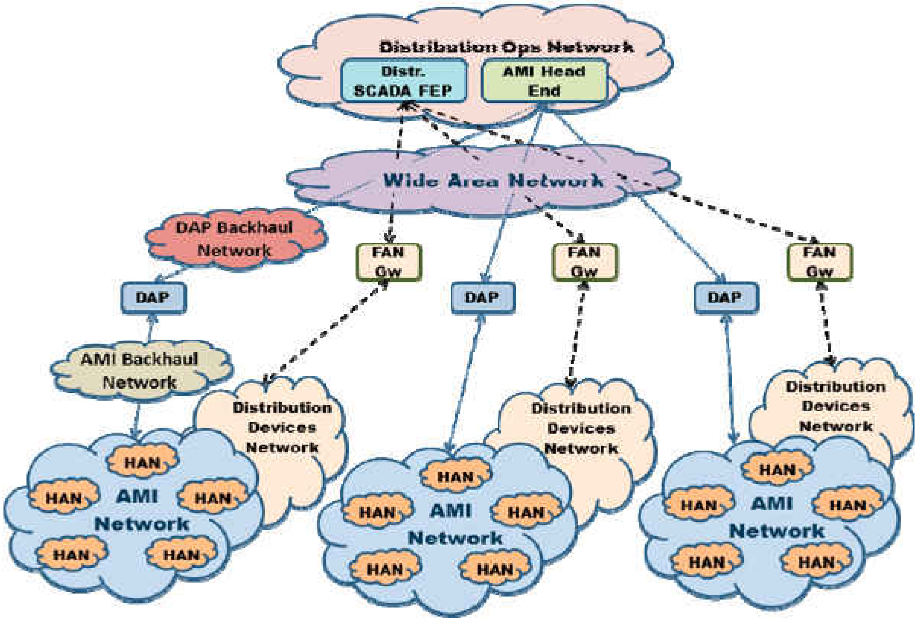


Figure 1-5: NIST Smart Grid Distribution Operations Network with Sub-networks (2011)

A large number of the initial utility-specific telecommunications deployments were predominantly comprised of private unlicensed radio systems, such as low-frequency (sub 1 GHz) and bandwidth-constrained, radio-frequency (RF) mesh networks or high-frequency (above 1 GHz) and interference-prone point-to-point broadband radio solutions. These utility-owned and capitalized telecom networks, which struggled with either high last-mile latencies or poorly reliable signal coverage, were mainly proprietary AMI vendor implementations as well. As a result, these private and siloed AMI systems not only prevented smart meter or sensor data from being transported or shared between multiple networks in the FAN, such the Distribution Devices Network or other AMI vendor networks referred to in Figure 1-5, but also were typically supplied by a OT or IT vendor whose core competency was not in telecommunications.

Additionally, the initial cost and security advantages of owning a private telecom network are quickly diminishing when compared to the public carriers, who have modernized their infrastructures to support more reliable and secure wireless broadband connectivity and are offering more competitive cellular data rates to accommodate the growing machine-to-machine (M2M) and hyped Internet of Things (IoT) markets, which according to Cisco (2013) are expected to surpass 50 billion devices by the year 2020. Furthermore, with the leading US public wireless carrier networks rapidly deploying their broadband 4G long-term-evolution (LTE) IP-based software-defined-networks (SDNs) to cover the US map, it is not uncommon to find OT distribution automation (DA) systems with IP-enabled commercial-off-the-shelf (COTS) cellular radios that not only align well with future-proof IP standards-based IEEE 802.3 Ethernet and IEEE 802.11 Wi-Fi technologies, but have a far less likelihood of obsolescence and a lower total cost of ownership compared to the private proprietary unlicensed radio technologies, such as IEEE 802.15.4 (ZigBee, 6LoWPAN) and IEEE 802.16 (WiMAX) that lack the US mainstream customer adoption in the M2M or IoT spaces like Wi-Fi and 4G LTE technologies (Masters, 2011).

In addition to the performance, reliability, and future cost implications of the private proprietary telecom solutions that transport data from smart meters and sensor devices on the utility networks, another key disadvantage of these networks is the manner in which the physical, network, and logical layers of their communication protocols are tightly coupled together within the Open Systems Interconnection (OSI) network architecture framework, which models the internal data stack of each communicated bit of information into 7 abstraction layers. Table 1-2 depicts the OSI model, its equivalent TCP/IP model, and example protocols that are commonly implemented in the IT and utility sectors (Antoniou, 2007).

Table 1-2: 7 Layers of OSI model and TCP/IP Representation (adapted from Antoniou, 2007)

Layer	OSI Model	TCP/IP	Example Protocols
7	Application	Application	HTTP, FTP, Telnet, SMTP, DHCP, DNS, TLS/SSL, SSH, SNMP, XML,MIME, MQTT, DDS, AMQP, CoAP, REST, Modbus, DNP
6	Presentation		
5	Session		
4	Transport	Transport	TCP, UDP, DCCP
3	Network	Internet	IPsec, IPv4, IPv6
2	Data Link	Network Interface	IEEE 802.3, 802.11, 802.15.4, 802.16 Bluetooth, MAC, PDCP, RLC
1	Physical		

Within the traditional proprietary end-to-end telecom systems, there are often no protocol recommendations to encourage the decoupling of the logical layers 5-7 from the network layers 3-4 and the physical layers 1-2. Although the ESB technology offers this same type of decoupling between the physical, logical, and network OSI layers, which enables interoperability between OT and IT systems in the utility back-office, there has not been a similar type of decoupling outside the datacenter, such as on the electric grid infrastructure's telecommunications FAN.

1.1.5 Innovation Trends in Other Industries

Though the US utility industry has witnessed a variety interoperability and integration challenges within their present smart grid technology deployments, many other industries, such as consumer electronics, healthcare, social media, transportation, and defense, have already encountered and successfully addressed these shortcomings with new technologies in the IoT and Industrial Internet segments.

Starting with the consumer electronics space, the mass proliferation of the iPhone and Android-based smartphone platforms have not only provided ubiquitous access and connectivity to the internet via Wi-Fi and cellular networks, but also created Operating System (OS) ecosystems that are portals to simple downloading or developing of software applications, known as Apps. With their Android OS being an open-source variant of Linux, Google has faced little competition spreading their open-source ecosystem at the leading Asian smartphone manufacturers, which makes up the majority of the US handset market not served by Apple, Nokia, or Blackberry. This open-source movement has not only helped Android, but also helped other Linux-based OS communities create simple embedded software Apps running on low-cost COTS single board computers, such as a Raspberry Pi, which can be purchased for as low as $35 (Allied Electronics, 2013). Likewise, as demonstrated by the $59 ODROID, which has 10 times more processor speed and 4 times more memory than a Raspberry Pi, there will be continued rapid innovation in the consumer electronics space as long as yesterday's smartphone CPU chips are being leveraged for the components of the next-generation single-board computers (Hardkernel, 2014)

The relevance of these open-source consumer electronic innovations is not just for the potential enhancement of the smart grid utility device capabilities, but also for the introduction of a parallel, virtualized computing environment next to the core OS of the

OT hardware device, which can enable the flexibility of running virtual software applications essential for unlocking and decoupling the upper logical layers of the OSI stack. One such software application that has paved the way in other high-tech and transaction-intensive industries, such as social media and healthcare, is the technology known as message-oriented middleware (MOM). By using simple and lightweight MOM software clients on a virtual machine (VM), the abstraction, translating, and sharing application layer data can be enabled via publish-subscribe (pub/sub) message bus protocols. Similar to the ESB middleware that runs in the data center, the pub/sub message bus technologies have the added benefit of running in the data center and on COTS embedded devices that do not require heavy computing resources.

Since the healthcare and social media are mainly geared toward static and centralized system applications, the transportation and defense sectors were also considered due to their complex, dynamic, and distributed nature. With the strong adoption of open pub/sub MOM on heavy computing hardware, the transportation and defense sectors have commercialized and standardized these pub/sub implementations to fit their high-performance, mission-critical, autonomous, and scalable applications.

1.2 Problem Statement

As new emerging and consumer-driven technologies, such as solar PV’s, wind generators, plug-in EVs, smart appliances, and home automation applications, are being introduced and installed in sizable volumes in the US, the operation behavior of the electric grid will continue to evolve from its current state, which is characterized as a stable, static, and predictable one-way pipe, to its future state, which is anticipated to become a more volatile, dynamic, and stochastic bi-directional network. Despite the trajectory of this grid transformation, the current digital smart grid technologies being deployed by the US utilities, to replace the legacy analog electromechanical equipment, are incidentally creating data siloes on the electric grid infrastructure, as depicted in Figure 1-6, which is preventing interoperability between different vendor system solutions outside the utility central datacenter (Laval, Handley, Smith, & Canders, 2014). Consequently, this lack of interoperability and its associated siloes created between hardware, telecommunications, and software, are also a byproduct of the lack of convergence between the various specialized engineering disciplines, such as mechanical engineering, electrical engineering, and computer science, respectively.

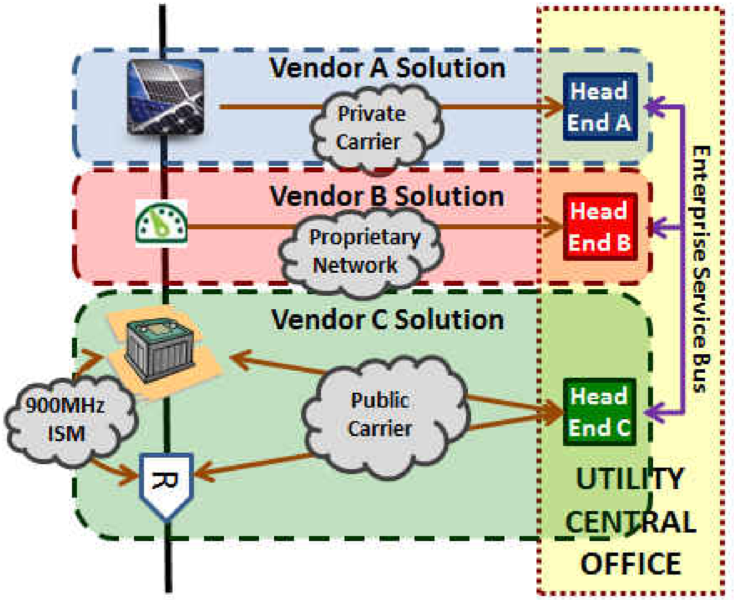


Figure 1-6: Example of Data Siloes between Different Vendors on the Grid (Laval et al., 2014)

This lack of interoperability between remote single-purpose assets in the FAN poses a problem for the future state of the grid, which is expected to embrace a higher penetration of dynamic and stochastic applications, such as DERs, that contain solar PV generation and energy storage. For example, if DERs were implemented in high volume fashion according to the current state of the grid, as demonstrated in Figure 1-7, then when an intermittent cloud passes over a solar PV, its measurement data would have to travel one-way and sequentially “pass-thru” the proprietary meter vendor’s AMI and associated backhaul telecom networks before arriving at the utility central office for translation by the required AMI head-end server, other back-office integration buses, and the OT control systems, and the response decision, along with model update, necessary to perform a command to remotely dispatch a battery (Laval et al., 2014).

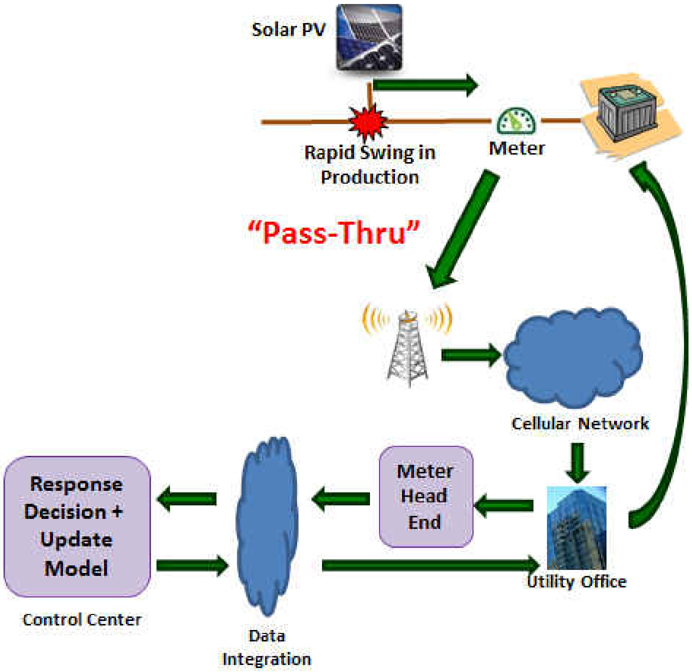


Figure 1-7: Example of a Centralized DER Control Scenario on the Grid (Laval et al., 2014)

Since the scenario described above in Figure 1-7, could take several minutes to process and execute, and the speed of clouds over a solar PV require response times less than a second, the lack of field interoperability with the neighboring battery storage system has prevented a quick local decision from being made. Additionally, the high latencies and data staleness resulted from the pass-thru telecom architecture have made this centralized application impractical. Furthermore, the cost and complexity of back-hauling all FAN asset data to the back-office systems is not maintainable and scalable as more and more data points are added to the OT and IT infrastructures.

1.3 Research Questions

Given the challenges identified in the problem statement with enabling interoperability between existing grid automation systems and the emerging DER technologies to be deployed more at US utilities in the future, the overall research question is centered around the idea of whether there is a way to translate and contextualize data in the FANs outside of the utility back-office data centers. Likewise, this question could be refined more narrowly by investigating whether is it possible to develop a framework that leverages commercially proven IT technologies in other industries to enable interoperability on the US electric grid infrastructure. Lastly, given that these relevant IT innovations were pioneered by other industries and were not optimized for the US utility industry, another important question would be whether a framework could be developed to combine the standardized utility data models with these new IT pub/sub middleware applications.

1.4 Research Contribution

The main contribution of this research is to provide a holistic view and framework that enables interoperability on the US electric grid infrastructure by leveraging standardized pub/sub protocols and existing utility data models, to translate data and contextualize information, respectively, between devices and systems on the FAN of the grid and outside of the back-office data center. The details of this overall research contribution are covered in the following two subsections: potential solution and potential contribution.

1.4.1 Potential Solution

The potential solution developed and validated in this dissertation in effort to solve the interoperability problem, exhibited in Figure 1-6, is known as the Field Message Bus (FMB), which abstracts the physical, network, and logical interfaces of OT device data outside the datacenter, as shown in Figure 1-8 below (Laval et al., 2014).

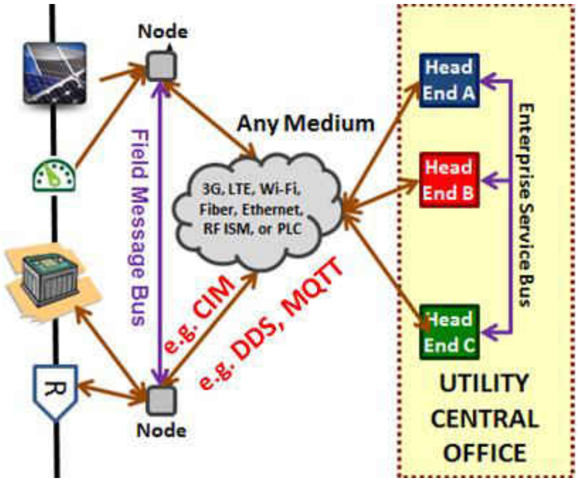


Figure 1-8: Proposed Field Message Bus Solution Implemented on the Grid (Laval et al., 2014)

In order to deliver the FMB interoperability solution proposed above in Figure 1-8, the combination of existing utility data model standards, such as the Common Information Model (CIM) along with the open standards-based pub/sub protocols, such as Data Distribution Service (DDS) and Message Queue Telemetry Transport (MQTT), should be implemented in a modular and seamless manner, while enabling secure access to local data on all grid nodes in the FAN. Consequently, with the proposed interoperability capabilities described above, the same example DER control scenario, which was previously depicted as a centralized path-thru system in Figure 1-7, can now be implemented in a distributed fashion, as shown in Figure 1-9, in order to perform fast peer-to-peer decisions on the FMB between the solar PV and battery storage, while also directly notifying the utility control office of the model update (Laval et al., 2014).

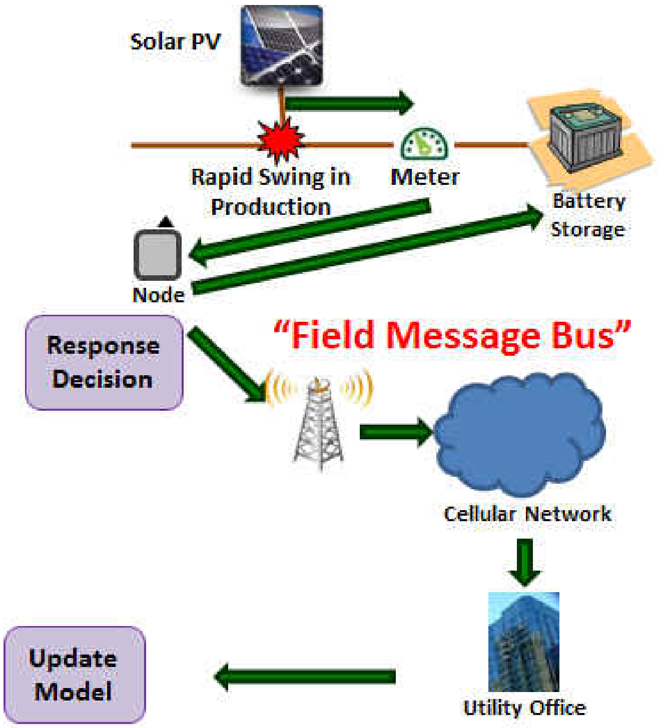


Figure 1-9: Example of a Distributed DER Control Scenario on the Grid (Laval et al., 2014)

1.4.2 Potential Contribution

Not only does this research propose a potential technology solution for enabling interoperability on the US electric grid, it also contributes a development methodology for leveraging industrial engineering tools in order to define requirements for a reference architecture and use-case application framework, which are instrumental for simplifying the process of implementing and validating interoperability in a case study. Moreover, the novel approach of employing industrial engineering best practices in order to simply the complexity of integrating the electric grid key components, such hardware, telecommunications, and IT software, is essential for breaking down the functional siloes created by the various disparate specializations in mechanical engineering, electrical engineering, and computer science, respectively. Lastly, it is also envisioned that the contributions from this framework can be extended by other researchers or industry stakeholders in effort to drive the adoption and potential standardization of an open Field Message Bus paradigm within the US utility industry.

1.5 Dissertation Outline

This research is organized in six chapters. Chapter One provides an extensive introduction to the trends inside and outside of the electric utility industry, while also providing the motivation behind this interoperability research. Chapter Two dives into the literature review of interoperability, message-oriented middleware, and common semantic model standards. Chapter Three reveals the methodology that fills the research gap and delivers the solution. Chapter Four describes the development of the interoperability framework. Chapter Five highlights the case study used to demonstrate the use-case application framework. Chapter Six validates and analyzes the results of the proposed interoperability framework. Chapter Seven wraps up with a conclusion and provides recommendations for future research work.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This literature review is split up into three subject areas to address the underlying problem statement of how enable interoperability of the utility operational and information systems that can provide a safe, reliable, affordable, sustainable, resilient, and flexible electric grid infrastructure. The first section introduces and defines the various types of interoperability and the value it can unlock from previously siloed data in proprietary systems. The second section presents the concept of message-oriented middleware (MOM), which is a subset of service oriented architecture (SOA), and its enabling technologies, the enterprise service bus (ESB) and publish-subscribe (pub/sub) message bus protocols. The third section digs into the various common semantic model standards considered by utilities and the efforts to implement and harmonize them in the North America utility sector. The fourth section summarizes the findings of this literature review and performs a research gap analysis in order to review the focus areas and reveal the novelty of the proposed framework.

2.2 Interoperability

Interoperability is essentially the ability to share and exchange information between multiple systems, but also be able to work together to execute an operation or perform a complimentary function. However, there have been many interpretations of this definition that have caused confusion regarding the true meaning of interoperability, especially as it relates to large, complex, and evolving systems, such as those in the US electric utility sector. The following sections will provide the various definitions, methods, and potential value achieved with interoperability.

2.2.1 Definitions of Interoperability

The Institute of Electrical and Electronics Engineers (IEEE) defines interoperability as the "capability of two or more networks, systems, devices, applications, or components to externally exchange and readily use information securely and effectively" (p. 3, 2011). In addition, in the context of the smart grid, the IEEE defines interoperability as providing organizations the capability to communicate and exchange meaningful data across different information systems, geographic regions, and culture, while consisting of hardware and software platforms to enable machine-to-machine (M2M) communications, well-defined data formats or syntax, and a common understanding of the content meaning or semantic (2011).

The US Department of Defense [DoD] (2010) defines interoperability as "the ability to operate in synergy in the execution of assigned tasks" and "the condition achieve among communication-electronic systems or items of communication-electronics equipment when information of services can be exchanged directly and satisfactorily between them and/or their users" (p.132-133). In the context of the military, Nitschke (2009) describes it as "the ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces and to use the services exchanged to enable them to operate effectively together" (p. 36). Knight, Widergren, Mater, and Montgomery (2013) claim that interoperability has been an integral part of military operations dating back to the Roman empire, where the coordination of army logistics through messaging was critical for success.

The European Commission (2004) defines its European Interoperability Framework (EIF) as a set of agreed-upon standards and guidelines that organizations reference when interacting with each other, but should not be static and it expected to evolve with changes to technologies, standards, and administrative requirements. The European Committee for standardization also defines interoperability is ‘‘a state between two applications when, for a specific task, an application can accept data from the other to perform this requires appropriate and satisfactory manner without this an external operator intervention’’ (Altran, 2010, as cited in Doumbouya, Kamsu-Foguem, Kenfack, & Foguem, 2014).

Zhao and Xia (2014) define interoperability as “a firm’s ability to manage disparate information systems (IS) with trading partners in its extended value network” (p. 273). Longhorn (2011) defines interoperability as the “ability of diverse systems and organizations to work together” (p. 35). Longhorn also points out that it goes beyond ‘data’ sharing and requires ‘systems’ to be capable of interoperating with open interfaces (2011). Ondimu and Muketha (2012) declare that interoperability “is achieved when all components and sub-systems in distributed systems work together seamlessly to achieve a set objective” (p. 620). Van Lier (2013) refers to interoperability as a “linguistic compound” that has dual meanings implied by the ‘inter’ term, which represents the application of mutual linkages between systems and designed entities, and the ‘operability’ term, which signifies the choreographing process or productive execution of the shared data exchange (p. 74).

2.2.2 Methods of Interoperability

The IEEE (2011) describes the architecture principle for interoperability as “the standardization of interfaces within the infrastructure is organized such that the system can be easily customized for particular geographical, application-specific, or business circumstances, but customization does not prevent necessary communications between elements of the infrastructure” (p.7). Other principles, that compliment interoperability, identified by stakeholders in GridWise Architecture Council, EPRI IntelliGrid, and NIST, include standardization, openness, security, extensibility, scalability, manageability, upgradeability, shareability, ubiquity, integrity, and ease of use (2011).

Zhao et al. (2014) asserts that interoperability within a heterogeneous mix of software, hardware, and system architectures is only possible when a common language is used and defined by interorganizational systems (IOS) standards that specify technical data formats and computer communication protocols. In addition, they argue that firms that adopt IOS standards can develop interoperability via two paths: internal capability building and community readiness across firm boundaries (2014). Hellberg and Grönlund (2013) emphasize that interoperability deals with technical system issues of connecting computer systems, but also takes into account the non-technical factors, such as social, politic, and organizational, that influence the end to end performance between disparate systems. Moreover, Pollar's study was utilized to identify communication, coordination, cooperation, collaboration, and channel as the five interoperability interaction types or variables needed to be analyzed when determining the value of interoperability (as cited in Grilo & Jardim-Goncalves, 2010). Furthermore, Ondimu et al. (2012) proposed a framework that qualitatively measured and ranked the following issues in distributed systems interoperability: ownership, funding, legacy, security, tooling, and ambiguity.

Grilo et al. (2010) developed a business interoperability framework geared for Architecture, Engineering, and Construction (AEC) companies to address the connections between business processes of each organization, while considering the compatibility of employee's values and internal culture. They also state that "interoperability is achieved by mapping parts of each participating application's internal data structure to a universal data model and vice versa" (2010). Moreover, any application can be mapped and interoperable with other participating applications as long as the universal data model is open and not proprietary, and ultimately eliminates the costly integration process between applications, especially as revisions and new releases are introduced (2010). Ondimu et al. (2012) felt that a common, standardized data format in an open database was a potential interoperability strategy for easing future interpretation, even in the event of a technological change, since the models are independence of hardware, operating system, and programming languages.

In the context of enabling interoperability in ultra large scale systems, Rezaei, Chiew, and Lee (2014) assessed a maturity model that also included technical, syntactic, semantic, and organizational types of interoperability. ISSA (2012, as cited by Azuara, González, & Ruggia, 2013) provided the following types of interoperability in the context of social security information exchange: political, legal, organizational, semantic, and technical. EIF's three dimensions include also organizational levels, semantic levels, and technical levels of interoperability, while enforcing the underlying principles, which include accessibility, multilingualism, security, privary, subsidiary, and the use of open standards (European Commission, 2004).

Hellberg et al. (2013) refers to technical interoperability as the "standardization of data flows" at the syntactic level. Iroju, Soriyan, Gambo, and Olaleke (2013) explained the importance of the consistency within the network layer, transport layer, application protocol layer, message protocol layer, and message sequencing in the context of achieving syntactic interoperability of electric healthcare records. However, since these syntactic level features mainly ensure the delivery of a message, it cannot guarantee complete processing and interpretation of the content by the receiving system without satisfying semantic interoperability (2013). Doumbouya et al. (2014) revealed that, in the context of the telemedicine field, messaging standards that support only syntactic interoperability are generally tailored as structured message transmissions, while the other standards, which satisfy both syntactic and semantic interoperability, document the clinical structure and coded terminology content to ensure unambiguous interpretation.

Gaynor, Yu, Andrus, Bradner, and Rawn (2014) define semantic interoperability as the process when structurally defined data with contextual meaning is exchanged and understood between applications. They also claim that semantic interoperability is a necessary, but not sufficient, condition for modularity, which is the ability to break down a complex system into clearly defined building blocks with well-specified interfaces that allows systems to be designed and integrated with best in breed components and enables quick and flexible software development life cycles (2014). Gaynor et al (2014) found that standards, a common application programming interface (API), and data mediators were three potential ways to records deliver semantic interoperability between electronic medical record applications that are internet protocol based. Zhao et al. (2014) claim that open integration standards are needed to synchronize information exchange and more effectively coordinate with multiple partners in order to better adapt to a dynamic business environment and new evolving technologies.

Depicted below, Turnista (2005, as cited by Tolk, Diallo, & Turnitsa, 2007) developed the following tiers of the Levels of Conceptual Interoperability Model (LCIM):

- Level 0: No interoperability
- Level 1: Technical interoperability at the communication protocol level
- Level 2: Syntactic interoperability between common data formats
- Level 3: Semantic interoperability between common content meaning
- Level 4: Pragmatic interoperability in the understanding of data context
- Level 5: Dynamic interoperability in comprehension of state changes
- Level 6: Conceptual interoperability in full interpretation and abstraction

Tolk et al. (2007) explained that the lower levels of interoperability, such as technical and syntactic, that cater toward network integratability, can be achieved with process driven IT technologies, such as Service-Oriented Architecture (SOA), while the middle tiers, such as semantic or pragmatic, can be attained with model-driven ontologies or taxonomies, but the upper tiers, such as the dynamic and conceptual levels, are still in the research and development phase.

2.2.3 Value of Interoperability

Iroju et al. (2013) states that the lack of interoperability in the healthcare system not only results in increased costs, high error rate, and knowledge mismanagement, but could also translate to a higher mortality rate. They conclude that the benefits in the healthcare industry, as a result of complete interoperability, include easy access to patient records, easy comprehension of medical terms, reduction in medical errors, reduced healthcare costs, integration of health-related records, and enhanced support for management of chronic diseases (2013). Walker et. al (2005) assessed the value of interoperability in the medical field and estimated that a full standardization of health care information exchange and interoperability (HIEI) could yield a potential net savings of $77.8 billion annually, which roughly makes up about 5% of the total health care spending in the United States.

Brunnermeier and Martin (2002) studied the impact of imperfect interoperability in the US automobile supply chain and found that it cost the industry roughly $1 billion per year and also added at least a 2 month delay to the launch of new vehicle models. Over

85% of the cost was made up of predominantly mitigation costs, associated with poor translations, reworking, and tooling, while an additional 5% was due to avoidance costs as a result of redundant software licenses, maintenances ,and training, and the remaining 10% was a result of time to market delays (2002).

Jardim-Goncalves, Popplewell, and Grilo, (2012) introduced the concept of the sustainable interoperability in the context of enhancing the quality, efficiency, and robustness of enterprise systems interoperability to prevent excessive IT resources, in both manpower and time, needed to support and maintain the integration interfaces that often break as a result of dynamic operational systems and complex networks. In addition, They also concluded that sustainable interoperability provides discovery capabilities, learning capacity, adaptability, transient analysis, and network notifications (2012). According to Real-Time Innovations [RTI] (2012), the goal of interoperability is to not only reduce the upfront procurement and deployment cost of IT systems, but more importantly the long-term support costs throughout its lifecycle. Schneider (2010) and Distributed Management Task Force (2003), both conclude that the interoperability yields the crucial scalability that prevents the increasing integration effort and potential cascading complexity of the system that is typically consumed by tying together the inconsistent data representations of the various silos created by disparate technologies.

According to Grilo et al. (2010), in order for companies to maximize the value and benefit of their Information and Communication Technology (ICT), which is an innovation enabler, they must improve and enhance interoperability between these ICT systems. Loukis and Charalabidis (2013) modeled and demonstrated that the adoption of Information System (IS) interoperability standards increases the impact of Information and Communication Technology (ICT) on a firm's business processes performance, value offered to customers, innovation activity, and financial performance. Van Lier (2013) postulates that connectivity to human-to-machine (HMI) and M2M systems is enabled by information interoperability, which is essential for assigning meaning within organizations necessary for the creating of new sharing opportunities and for allowing the scaling with growing data exchanges between random autonomous systems and existing static objects in the network. In addition, Simmons (2011) points out that the lack of interoperability not only leads to problems when software applications are from different vendors, but even with multiple versions of the same software from the same vendor.

Van Lier (2013) claims that delivering interoperability is a prerequisite for situational awareness, especially in complex situations where certain functions depend on critical information in order to perform their assigned task properly, such as those in command and control applications and operating room cases. Longhorn (2011) emphasizes the critical need of interoperability standards to enable and deliver situational awareness of cross-boundary information sharing, which requires both technical standards and international accredited agreements for data accessibility. Additionally, it was disclosed that the value of interoperability standards in the area of geospatial systems can be achieved from cost savings, increased operational efficiency, and most importantly, the saving of lives (2011). Chenine, Ullberg, Nordstrom, Wu, and

Ericsson (2014) claim, that when interoperability issues do occur, the distance to integrate between the measurement source and the application is increased at both the geographical and organizational dimensions as a result of additional protocol conversions and network configurations that can transpire within an internal communication gateway or external to a systems operator.

2.3 Message-Oriented Middleware

Message-Oriented Middleware (MOM) is a software enabler that encapsulates and stores data in the form of a message that allows asynchronous communications and messages queues exchanges between a sender and a receiver between distributed systems (Maheshwari et. al, 2004, as cited in Valls and Val, 2013). It is subset of the paradigm, Service-Oriented Architecture (SOA), and is commonly used as a method to abstract the complexity of integration and enable interoperability between diverse systems that have different application programming interfaces (APIs) and wide-scale heterogeneous networks. Since MOM has many different flavors and spans across a plethora of IT applications, the scope of this concept as it pertains to this literature review has been limited to areas that exist today in the US utility sector. Therefore, this section on MOM will serve to first briefly introduce the concept of its superset, SOA, then followed by more elaborate studies on its subsets the Enterprise Service Bus (ESB) and pub/sub message bus protocols.

2.3.1 Service-Oriented Architecture

The Organization for the Advancement of Structured Information Standards (OASIS) defines Service-Oriented Architecture (SOA) as “a paradigm for organizing and utilizing distributed capabilities that may be under control of different ownership domains” (2006, as cited by Abousba and El-Sheikh, 2008). Dori (2006) describes SOA as a collection of distributed and self-contained web services that decouple the business logic from the user interface, integration logic, and process logic. In other words, SOA is a process-oriented software middleware that is loosely coupled to object-oriented software to orchestrate applications or functions as services within a system of systems (SoS). These services are agnostic to the vendor or technology implementation and are designed to handle a significant number of simultaneous transactions that can determine the appropriate routing and data sharing interactions between the necessary systems. King (2008) claims the energy industry took advantage of SOA to gain better operating flexibility since the business environment for managing enterprise integration projects for the electric distribution system operations was continually changing and evolving. It also was a stop-gap to reduce the escalating integration costs and complexity that was a byproduct of many disparate and siloed proprietary systems, new and legacy (2008).

2.3.2 Enterprise Service Bus

One of the most commonly used SOA MOM implementations in the utility back-office is called the Enterprise Service Bus (ESB). Similar to reasons why an interoperable open architecture (IOA) SoS was employed by the US DoD or UK Ministry of Defense, the ESB middleware services are intended to flatten a company's integration strategy by shifting it from a vertical one to a horizontal one (Real-time Innovations, 2012). Figure 2-1 illustrates the evolution of moving from proprietary, customized interfaces to modular ESB middleware interfaces in an utility back-office (adapted from EPRI, 2012).

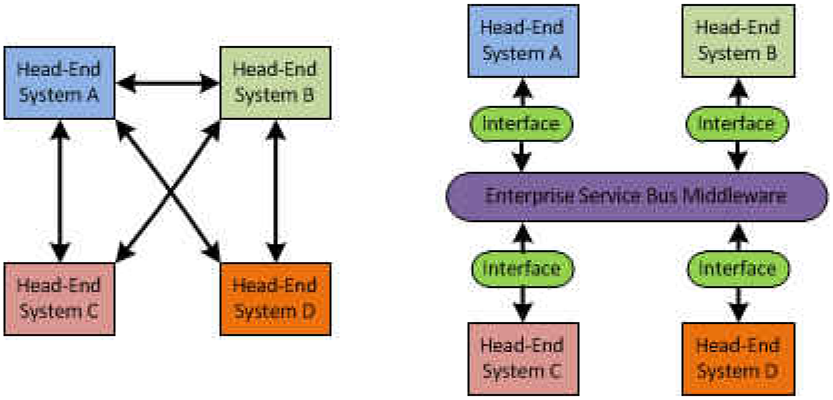


Figure 2-1: Point-to-Point Enterprises and Enterprise Service Bus (adapted from EPRI, 2012)

Gray and Flowers (2012) concludes that the "distance to integrate" or overall cost of integration reduces greatly as utilities gain more experience and governance maturity with ESB mediation layers between applications that leverage a common data reference model like Common Information Model (CIM). Moreover, the more interoperable the ESB interfaces are with a common schema, the shorter the "distance to integrate" will be required and the closer to plug-and-play interchangeability can be achieved for lowest overall lifetime costs (2012). However, this lowest cost plug-and-play capability can only be accomplished if both a ESB and an Enterprise Semantic Model (ESM) are used together to reduce the number of point-to-point data transformations from N*(N-1) to N (Sisco, 2003). Without both, it is not uncommon that an organization may employ multiple separate ESB's that not only require custom interface bridges between them, but also are implemented and supported by different IT middleware vendors (2003).

To combat the large number of early proprietary ESB implementations, other transaction-intensive industries, such as investment banking, healthcare, and social media, have already paved the way for better consistency on their ESB middleware, by adopting a similar IOA that was developed for the military, which also embraced the flexibility to wrap legacy systems that were not initially developed to integrate at all with the new open architecture (RTI, 2012). By enforcing open-source principles in those data-intensive industries, ESB technology has been proven to demonstrate meaningful interoperability and integratability in a IOA-based SoS, while at the same time, enabling modularity, portability, replaceability, extensibility, and most importantly, interchangeability, which yields true plug-and-play interfaces (2012). However, the sheer decision to administer and implement the open-source ESB by itself does not guarantee an interoperable IOA-based SoS, and relies on evaluating and selecting the appropriate message bus protocols for the SOA MOM orchestration engine that is responsible for discovery and delivery of the translated data between nodes (Schneider & Farabaugh, 2009).

2.3.3 Message Bus Protocols

The orchestration engine of the many ESB technologies is predominantly handled by MOM in the form of message bus protocols, which are classified in three general categories: client/server, message passing, and publish-subscribe (Schneider et al., 2009). Client/server and message passing protocols have been traditionally used extensively by utilities and other industries due to the static, structured, centralized nature of their existing information systems. However, unlike publish-subscribe (pub/sub) message bus protocols, client/server and message passing protocols do not contain the “data-centric” models that are required for managing distributed applications (2009). Moreover, since the electric grid infrastructure of the future necessitates a hybrid SoS that includes dynamic and distributed decisions, the pub/sub messaging topology is more appropriate for this research due to its flexible interaction models for remote decoupled components that provide high reliable and timely data exchange (Valls et al., 2013).

Outside of the commercial sectors, the innovation of open-source pub/sub message bus protocols is primarily being driven by consumer markets dominated by the Internet of Things (IoT). As a result, a handful of these pub/sub messaging protocols have emerged as a standards-based Commercial-Off-the-Shelf (COTS) MOM software technologies and are in the process of being more understood and tailored for industrial automation applications that are connected and controlled via the internet (Corsaro, 2013). In addition, since there is not a one-size-fits-all pub/sub protocol, a combination of multiple different protocols, that are bridged with protocol adapters, has been a way to manage the evolution of a legacy system without the need to re-architect the integration of the distributed information system (Foster, 2014). Figure 2-2 on the next page displays the various IoT messaging options (adapted from Foster, 2014).

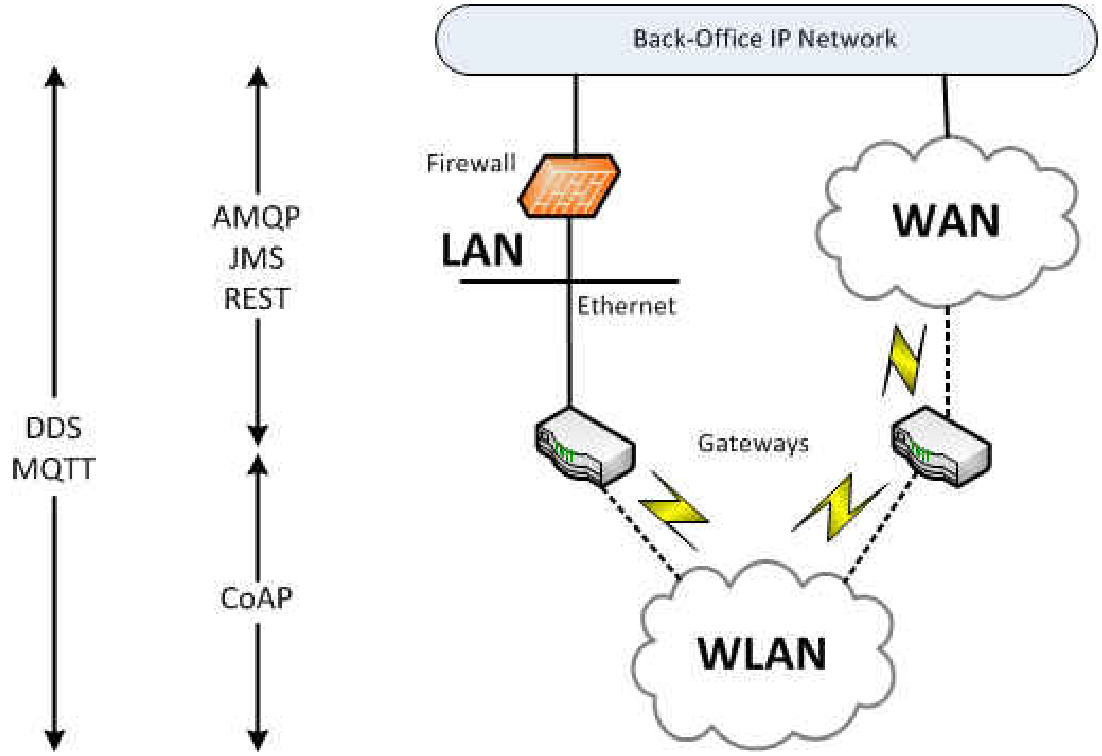


Figure 2-2: Message Bus Protocols as it Relates to the IoT Segment (adapted from Foster 2014)

Of the standardized open-source IoT technologies illustrated in Figure 2-3, Message Queue Telemetry Transport (MQTT), Advanced Message Queue Protocol (AMQP), Java Message Service (JMS), and Data Distribution Service for Real-time Systems (DDS) are the only four protocols in the diagram that are classified as pub/sub messaging middleware. Within these four pub/sub protocols, there are several major differences that distinguish each technology from each other and dictate the appropriate use-case or application for each protocol. The key attributes to compare the various protocols, shown in Table 2-1, include the type of broker topology, performance, footprint, coupling, usability, API, and Subscription (adapted from Foster, 2014).

Table 2-1: Comparison of the IoT Pub/Sub Middleware Protocols (adapted from Foster, 2014)

	MQTT	AMQP	JMS	DDS
Topology	Broker	Broker	Broker	Broker-less
Performance (Msg/sec)	1000-10000's	1000-10000's	1000-10000's	100000+
Footprint	Embedded & Server	Server	Server	Embedded & Server
Coupling	Loosely	Loosely	Tightly	Decoupled
Usability	Simple	Moderate	Simple	Complex
API	Customized	Customized	Standardized	Standardized
Subscription	Topics	Queues & Exchanges	Queues & Topics	Topics

In reviewing Table 2-1, topology is the first attribute and most signifying distinction for each pub/sub message bus protocol and will be examined in more elaborate detail in the following two subsections. As for the performance, when comparing the broker-based implementations of MQTT, AMQP, and JMS versus the broker-less topology of DDS, there is a direct relationship with performance as the broker protocols, MQTT, AMQP, and JMS are limited to 10,000's of messages per second per subscriber, while the broker-less and "data bus" protocol, DDS, can scale well above 100,000 message per second per subscriber (Foster, 2014). In terms of the hardware computing environment, MQTT and DDS can both fit in each an enterprise server or a low-cost COTS embedded computing environment, while AMQP and JMS are consume heavier computing resources and require an enterprise server setting. In regard to coupling type, MQTT and AMQP are loosely coupled, JMS is tightly coupled, and DDS is decoupled, which essentially means that MQTT, AMQP, and DDS have interoperable wire protocol interfaces, while JMS does not (2014). In terms of usability, MQTT and JMS are simple to implement, while AMQP is moderate and DDS is complicated and not easy to implement. In evaluating each API, only DDS and JMS have a pre-defined standardized API, while MQTT and AMQP do not (2014). Last, but not least, the MQTT and DDS manage transactions via topic subscription, while AMQP and JMS utilize queues along either exchanges or topics (2014).

Each pub/sub messaging protocol has its strengths and weaknesses, but for the purposes of this research, it is evident that JMS is not an appropriate protocol for this research due to its tightly coupled interface that hinders its interoperability with other JMS vendor protocol implementations. On the flip side, MQTT, AMQP, and DDS each potentially offer interoperability to some degree with their loosely coupled or decoupled interfaces that allow translation between other vendor's protocol implementations. Therefore, these three identified interoperable pub/sub protocols, will be reviewed further with respect to their categorized topology: broker-based and broker-less.

2.3.3.1 Broker-based Publish-Subscribe Middleware

In exploring the academic research community on publish-subscribe (pub/sub) middleware, there were limited studies on broker-based pub/sub protocols and even fewer publications on the open standards-based pub/sub protocols, AMQP and MQTT, despite their recent growing adoption in the consumer and commercial IoT segments. Figure 2-3 on the next page shows a conceptual diagram of a broker-based pub/sub message bus implementation (adapted from Foster, 2014). As depicted, the broker is positioned to mediate the flow of data traffic from the publisher, by storing, prioritizing, and routing messages, to the subscriber. Functionally, broker-based protocol's main role is to abstract the network complexity of the publisher from the application interfaces of the subscriber, in order to reduce the possibility of vendor "lock-in" (Vinoski 2006). Schneider (2010), Foster (2014), and Corsaro (2013) all label the broker-based pub/sub protocols as "message-centric," which infers that mainly syntactic interoperability can be guaranteed.

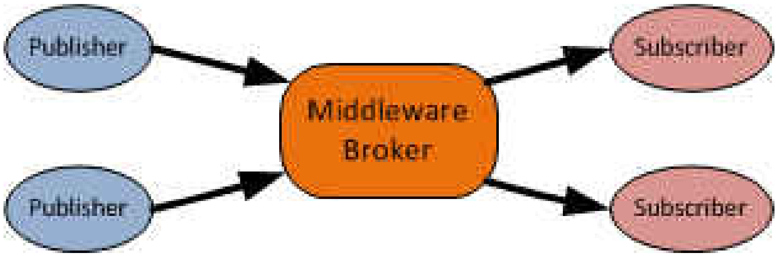


Figure 2-3: Broker-based Message Bus (adapted from Foster 2014)

In examining the open-standard interoperable pub/sub middleware, AMQP, it was initially developed in the enterprise data-center setting for the financial trading and banking sector, which requires high levels of performance, scalability, reliability, and manageability (Vinoski 2006). Moreover, AMQP not only can queue and optimize routing decisions, but it can also enforce rules for enhanced robustness and fault-tolerance, while packing more data inside its binary format for high throughput (2006).

On the other hand, the other open-standard interoperable pub/sub middleware, MQTT, is lightweight and tailored for low-end, bandwidth-limited telemetric devices (Hunkeler, Truong, & Stanford-Clark, 2014). In addition, MQTT was designed to offload the routing or networking complexity to the broker's side, while making it simple to use and implement on the client’s side (2014). However, the disadvantages of MQTT are that the broker cannot handle many device endpoints and also it is a single-point of failure with limited quality of service (QoS) options needed for fault-tolerance (2014).

2.3.3.2 Broker-less Publish-Subscribe Middleware

Unlike the broker-based pub/sub topology that had few academic literature, there were many journal articles on broker-less pub/sub middleware and particularly on the open standard-based message bus protocol, DDS, which has been referred to as the defacto middleware standard in military applications (Serrano-Torres, Garcia-Valls, & Basanta-Val, 2013). Figure 2-4 below shows a conceptual diagram of a broker-less pub/sub message bus implementation which, exhibits a flat data bus that connects data traffic between publisher and subscribers (adapted from Foster, 2014). Similar to a broker-based protocol, that stores, prioritizes, and routing messages between publisher and subscriber, the broker-less data bus middleware sits virtually on both the publisher client side and subscriber client side. Schneider (2010), Foster (2014) and Corsaro (2013) each refer to DDS as being a “data-centric” protocol, which infers that it can enable both syntactic and semantic interoperability.

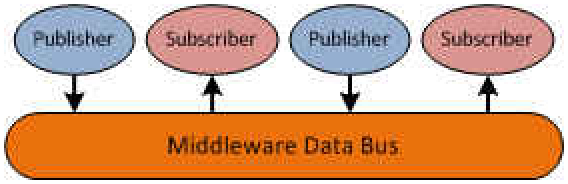


Figure 2-4: Broker-less Message Bus (adapted from Foster 2014)

In Figure 2-5 below, an adaptation of Foster (2014) illustrates how the broker-less topology provides a very high level of abstraction, known as a "global data space," that forces the user to pre-define topics that inherently understands the semantic context and delivers a consistent view of the data to the subscriber (Corsaro, 2013). Moreover, RTI (2012) refers to this global data space as a "system data dictionary" that includes meta-data that defines the semantic model for every piece of information and allows it to be re-contextualized to any application or service that subscribes to it. Furthermore, Schneider (2010) concludes that a crispy defined information or semantic model is mandatory for effectively implementing and benefitting from the content-aware and data-centric nature of DDS.

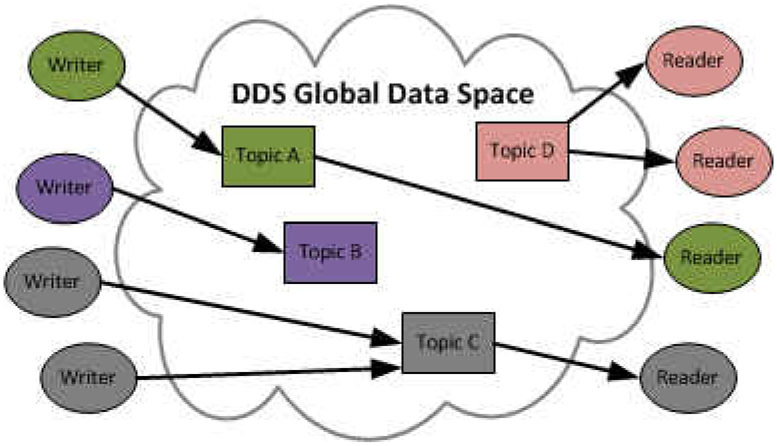


Figure 2-5: DDS Data Space for Contextualizing Messages (adapted from Foster, 2014)

DDS has been standardized by the Object Management Group (OMG) organization, which has facilitated and ratified a DDS interoperability (DDSI) specification, known as Real-Time Publish Subscribe (RTPS), that allows and ensures any compliant DDS implementation to interconnect to any other vendor implementation's DDSI-RTPS-compliant data-space without exposing any sensitive information between the disparate domains (Lopez-Vega, Povedano-Molina, Pardo-Castellote, & Lopez-Soler, 2013). DDS has also been a common middleware theme in distributed, real-time, and embedded (DRE) systems due to their model-driven implementations being capable of leveraging the standard DDS application programming interface (API) for high flexibility and reusability in different functional contexts, which enable iterative refinements and extensions of both applications and middleware independently on the DREs (Hugues, Pautet, & Kordon, 2006).

Hakiri, Berthou, Gokhale, Schmidt, and Gayraud (2013) also enhanced a DDS implementation for DRE systems by providing end-to-end quality of service (QoS) policies that can optimize processor scheduling via bandwidth control and latency predictions. Wang, Schmidt, van't Hag, and Corsaro (2008) proposed a framework for network-centric operations and warfare (NCOW) systems that has the potential to enhanced the QoS capabilities of DDS by introducing adaptive discovery services that enable large-scale, secure, distributed, and embedded NCOW systems in heterogeneous and dynamic wide area network (WAN) ecosystems. Al-Madani, Al-Saeedi, and Al-Roubaiey (2013) also utilized the QoS features, within DDSI-RTPS protocol standard, to developed a scalable approach to stream real-time video data over wireless local-area-networks (WLAN) by dynamically stabilizing video bandwidth without time-varying packet error loss or visible interruptions to reduce wireless network congestion. Lopez-Vega et.al (2013) addressed DDS's main scalability issue of interconnections between remote data-spaces by developing a DDSI-RTPS-compliant content-aware bridging service that performs data transformation and QoS adaptation of publish-subscribe information regardless of the software revision of the application or variances in the data structures and interfaces.

Serrano-Torres et al. (2013) successfully showed that DDS real-time middleware could be merged with virtualization technology in order to better position their large scale cyber physical systems that needs to be integrated with heterogeneous software and hardware, while also handling many nodes on different networks. The results of their experiment conclude that a virtualized environment can be combined with DDS with little or no impact to the performance and computing resources (2013). Gonzalez et al. (2011) developed and tested a custom lightweight implementation of DDS to prove that a real-time data-centric publish-subscribe middleware could fit on resource-constrained computing devices, such as wireless embedded sensors, that have a few hundreds of kilobytes of capacity. Their research exhibited advantages in ease of software portability and lower latency at the minor expense of throughput versus the commercial version of DDS that contained a heavier hardware footprint (2011).

2.4 Common Semantic Model Standards in the Electric Utility Sector

Crapo, Wang, Lizzi, and Larson (2009) proposed the notion that shared semantic models will become the foundation for smart grid interoperability. Moreover, Crapo, Griffith, Khandelwal, Lizzi, Moitra, and Wang (2010) went a step further by stating that shared and consistent semantic models prevent individual data sources from defining the semantics and syntax of the data. According to Sisco (2003), an agreement on a common data exchange model is not enough to ensure component interoperability in the utility sector, but rather needs further standardization on how the data is to be accessed. There have been many efforts to standardize common and shared semantic models in the utility space, but they have lacked the universal adoption rates as demonstrated in the telecommunications, healthcare, and manufacturing industries (King, 2008).

Industry standards for common shared definitions of nearly all assets and traditional operational systems are not new in the US power utility sector. In fact, legacy utility industry standardized models, such the International Electrotechnical Commission's (IEC) common information model (CIM) suite for transmission (IEC 61970) and distribution (61968), have already been around for several decades to define electric grid device assets. Furthermore, IEC 61850 has also been received attention recently due to its comprehensive object structure definitions for assets inside a transmission or distribution substation. Naumann, Bielchev, Voropai, and Styczynski (2014) reviewed a landscape analysis of all of the smart grid standards in the IEC Technical Committee (TC) 57 reference architecture and identified CIM (IEC 61970 and IEC 61968) and IEC 61850 as the most appropriate interoperability standards for smart grid protection automation.

2.4.1 Common Information Model

The Common Information Model (CIM) is a family of IEC standards, such as IEC 61968 for power distribution systems and IEC 61970 for transmission systems, that was developed to facilitate model-driven system integration via a common canonical data model that represents objects and entities in the electric power transmission and distribution (Saxton, 2013). As one of the most comprehensive and widely accepted models for power delivery, IEC CIM is categorized prominently as an information model and is anticipated to be preserved “as a set of ontologies within a federation of ontologies” (Crapo et al., 2010). Saxton (2013) referenced the GridWise Interoperability Framework to show that CIM plays an instrumental role in providing business context, semantic understanding, and syntactic interoperability within the internal and external functions of an organization.

In Figure 2-6, on the next page, Simmons (2011) presents a different view of CIM’s role by comparing the business context, semantic understanding, and syntactic interoperability categories to the information model, contextual model, and implementation model, respectively. Moreover, Simmons also divulges, shown in Figure 2-6, that CIM is a top layer information model that is not intended to be realized in its entirety and should be restricted to each profile’s context since there are several different methods and formats for defining the contextual model that can vary depending on the software modeling and code generation tools be used (2011). Lastly, it is also pointed out that CIM is not an implementation model since its serialized data structures are derived from contextual models (2011).

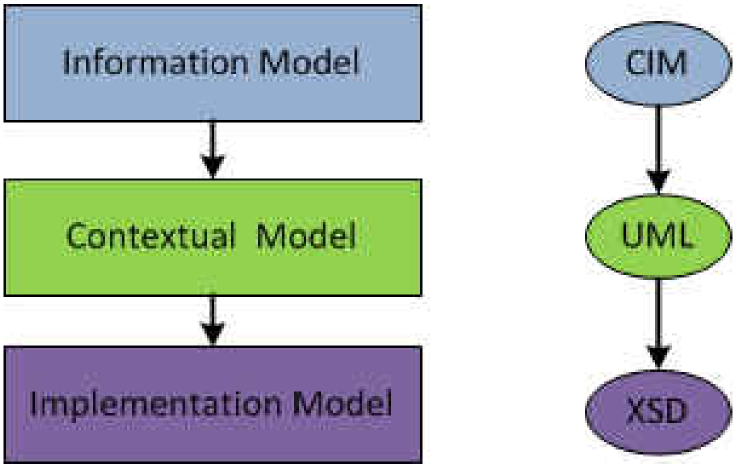


Figure 2-6: CIM and its Role in the Model Hierarchy (adapted from Simmons, 2011)

Saxton (2013) and Gray and Flowers (2012) both refer to CIM as the semantic vocabulary that defines the precise meaning of power grid attributes and entities and their basic relationships between each other. However, Gray et al. (2012) also criticized IEC CIM for being merely "a dictionary, not a writing guide" when it came to characterizing the ambiguous direction of using its extensive semantic reference model for system integration. Simmons (2011) supported this sentiment by asserting that the lack of introductory education materials was one of the major barriers preventing CIM from becoming pervasive standard. Furthermore, EnerNex (2014) reported that a large utility, DTE Energy, would have benefitted more from CIM if they would have had access to better collaboration tools, such as SharePoint or adhoc list servers, to help train its staff on the upfront training and provide documentation to bridge the knowledge gap on how to apply CIM for the first time.

The Distributed Management Task Force (2003) concluded that the goal of CIM schema was to abstract well-understood information with the possibly of being mapped into a technology-neutral myriad of databases, directories, or repositories. Since CIM was originally defined and built as an object-oriented model, it relies on inheritance, relationships, abstraction, and encapsulation to provide the information consistency and flexibility needed for data reuse and extensibility (2003). Saxton (2013) introduces Unified Modeling Language (UML) as a key differentiator for CIM that represents both a general information model and a semantic schema, which when tied together simplify system integration via its standardization of data source patterns between consumers and qualified producers.

Since IEC CIM requires a fairly deep understanding of UML class diagrams for defining the vocabulary as well as Resource Description Framework (RDF) schema for describing the relationships between classes, CIM has been perceived to be more confusing than a typical flat file format (Simmons, 2011). Likewise, CIM’s inherent nature of employing a super-class element for each common attribute by requiring a universally unique identifier (UUID), known in CIM as a master resource identifier (MRID), has been described as tedious to the extent that one utility coined the CIM UUID mapping process as “Giant Stupid Number mapping” (EnerNex, 2014). Moreover, Saxton (2013) compiled a list of other perceived complaints in Table 2-2, though not all true, that might have slowed the adoption of CIM. In summary, the CIM is viewed as a starter kit that requires a lot of manual governance to implement and evolve with an organization’s enterprise semantic model (ESM).

Table 2-2: Perception Concerns of CIM (Saxton, 2013)

Perceived Complaint	Fact / Reality
CIM is not stable	Requires version control of CIM UML
CIM is too complex to learn and contains to many irrelevant parts	CIM model is large and complex, but typical interface is only a very small subset
CIM requires an undesirable extra step in system integration mapping	Consequence of not mapping is lack of scalability
Vendors might not adopt CIM interface	Vendor should only know few parts of CIM
Do not want to convert all metadata to CIM	CIM is only a starter kit for ESM
CIM doesn't meet all interfaces	CIM UML is extensible and traceable

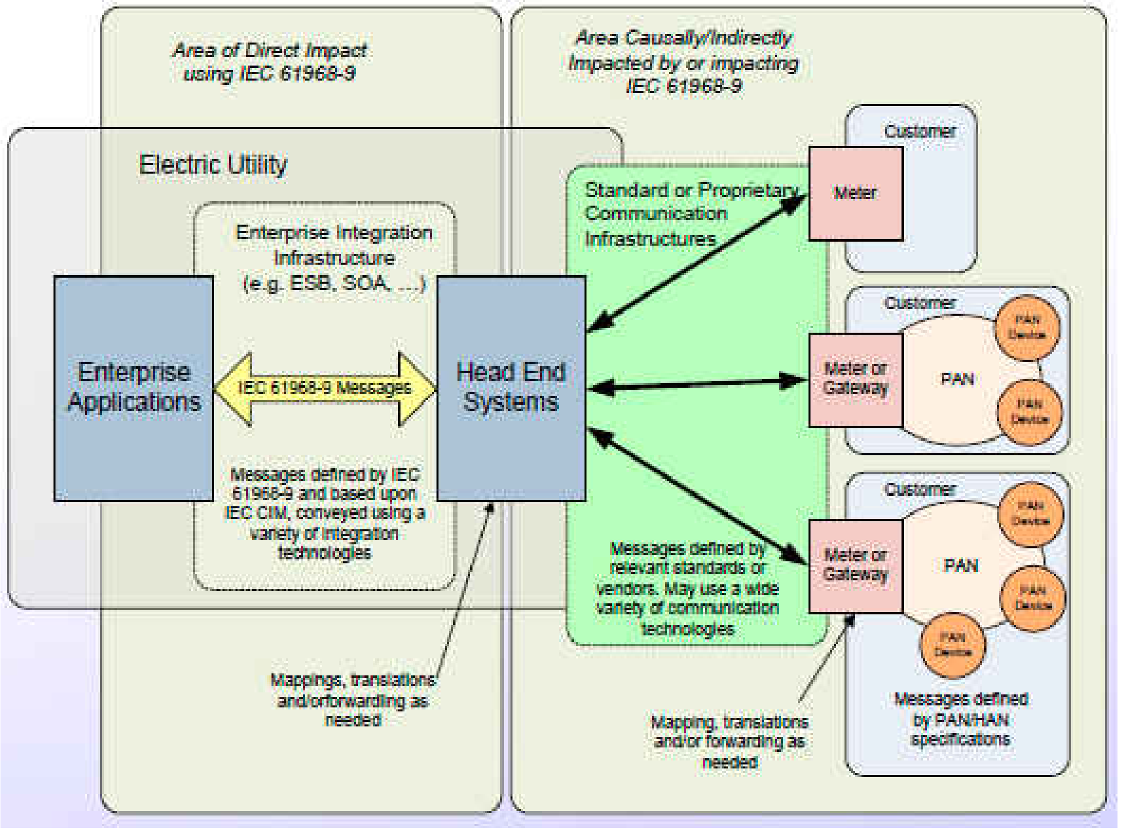


Figure 2-7: Benefits of IEC CIM in the Electric Utility Back-Office (Saxton, 2013)

As exhibited in Figure 2-7 on the previous page, the primary benefits and greatest impact that IEC CIM standards, such as IEC 61968, can offer the electric utility industry are mainly in the domain of back-office integration because the vast majority, if not all, of the object attributes and semantic relationships were derived assuming a static enterprise integration infrastructure that depends on a head end system in the picture to interface with and buffer the message traffic that is received from the proprietary or standard communication infrastructure (Saxton, 2013).

2.4.2 IEC 61850

Unlike CIM canonical data structures that sit behind a head-end system in an enterprise setting as depicted in Figure 2-7, the current applications involving IEC 61850 data models reside outside the data center in the substation Local Area Network (LAN) environment and have historically relied on heavy protocols that run exclusively on top of TCP/IP for OSI layers 3 and 4. Consequently, the protocols that the IEC 61850 standard supports are data intensive that require a high-speed wired Ethernet connection or wireless broadband communication medium, such as Wi-Fi (Moore and Goraj, 2010).

Bi, Jiang, Wang, and Cui (2013) demonstrated and validated the mapping of a substation automation system, using the semantic model defined by the IEC 61850 standard, to the real-time publish-subscribe middleware, DDS. Unlike the traditional communication protocols mapped with IEC 61850 that require TCP/IP over a broadband Ethernet LAN, Jiang et al. was able to implement a seven step process to employ a standards-based Interface Description Language (IDL) for the schema and Data-Centric Publish-Subscribe (DCPS) API for the syntax definitions to enable a low-latency, reliable, and deterministic message delivery middleware service that is independent of the communication network infrastructure and physical mediums (2013). Calvo, de Albeniz, Noguero, and Perez (2009) also showed that IEC 61850 object definitions for electrical protection relay products could be mapped fairly simply between two standards-based and platform-independent middleware technologies, Common Object Request Broker Architecture (CORBA) and DDS, since they had the same semantic representations in IDL.

Since IEC 61850 is focused on substation vocabulary, there has been challenges to re-use or extend its data models to other grid assets, especially those outside the boundary of a substation fence. Gaviano, Weber, and Dirmeier, (2012) explored the interoperability of IEC61850 and illustrated how its versatility and reliability could help deal with the rising penetration levels of distributed energy resources, but also noted the gaps in the standard's modeling details for photovoltaic (PV) inverters and energy storage that were still under development. Naumann et al. (2014) revealed that IEC 61850 by itself is not sufficient for advanced automation and protection schemes because the standard is mostly focused on communication between several single devices at a substation and also has gaps in the vocabulary as it pertains to specific device capabilities on power grid that are not defined in substation automation use-cases. As a result, Neumann et al. was forced to combine with CIM to take advantage of the comprehensive representation of the broader power grid elements that typically handled by the central control center, but encountered complexity in harmonizing the two standards due to CIM's centralized network topology and extensible nature, which required multiple type conversations and semantic mappings (2014).

Nieves, Espinoza, Penya, de Mues, and Pena (2013) developed a smart grid distributed intelligent node architecture to provide syntactic and semantic interoperability between nodes across three substations. Their prototype design of each node integrated multiple agents that maps global ontology profiles of IEC 61850 and CIM, while simultaneously enabling automatic reasoning capabilities, data streaming processing, storage repositories, and local decision-making in both real-time and near-real-time (2013). Though validated for a static vocabulary on the smart grid knowledge base, their approach was not designed to capture and support new dynamic domains, such as renewable energy resources, that would require a frequently updated ontology knowledge base in the form of CIM extensions (2013).

Santodomingo, Rohjans, Uslar, Rodriguez-Mondejar, and Sanz-Bobi (2014) proposed an ontology matching system that aligned both CIM and IEC 61850, using various matching methods and mapping algorithms to deliver bi-directional translations between the two standards in order to demonstrate interoperability between five substation architectures. However, their proposed methodology was not intended to be a generic matching ontology system that could automatically generate all alignments, and required manual importing of deep domain expertise from particular ontologies, such as the power system standards (2014).

Lee, Kim, Yang, Jang, Hong, and Falk (2014) developed a set of principles for analyzing IEC 61850 and CIM data types using a standard model transformation tool that could identify matching and non-matching types, unify the matching types, and revise the non-matching types to help improve interoperability. However, Lee et al. claims the insufficient UML and object-oriented background in the electric grid industry has contributed to the slow adoption of CIM and limited exposure for their unifying approach to gain traction on new evolving use-cases with advanced communication technologies (2014).

2.5 Summary and Research Gap

As described in the literature review, there has been a wide range of research on the topic of interoperability that spans across many industries that each have different definitions, methodologies, and perceived benefits of interoperability, despite the similar systematic challenges and characteristics faced in their respective large, complex, and dynamic environments. Overall, the studies that were further along with demonstrating the benefits of interoperability have achieved it at both the technical and organizational levels, which require standardization in open technological interfaces, contextual taxonomies, and inter-organizational business processes. Furthermore, since interoperability is a prerequisite for situational awareness, modularity, and scalability, it can be inferred that the US utility industry will benefit significantly from a framework that can enable interoperability on its electric grid infrastructure, which currently lacks these important traits needed for operational sustainability.

Additionally, as presented in the literature review, Service-Oriented Architecture (SOA) and Message-Oriented Middleware (MOM) have proven to improve and demonstrate low levels of technical and syntactic interoperability for the US utility industry in the form of a Enterprise Service Bus (ESB) with Common Information Model (CIM) semantic models, but have not extended the data integration capabilities outside an enterprise data center setting or considered translating and contextualizing data using open-standard publish-subscribe (pub/sub) middleware, which has shown success in the banking, healthcare, transportation, and defense sectors. Of the open-standard pub/sub message bus protocols, the broker-less middleware, Data Distribution Service for Real-time Systems (DDS), has been studied the most extensively in the academic setting and caters toward enabling semantic interoperability in a heterogeneous mix of dynamic, Wide Area Network (WAN) Information and Communication Technology (ICT) applications for distributed, real-time, embedded (DRE) systems, which are anticipated aspects in the future state of the US electric grid infrastructure.

With regard to common semantic models in the electric utility industry, CIM and International Electrotechnical Commission (IEC) 61850 are the two most commonly considered standards for interoperability, but still have a scarce adoption rate due to the utility industry's perceived misconceptions and lack of understanding of how to apply their strengths and work around their weaknesses. As for CIM, it is the most comprehensive vocabulary for the assets in the electric grid infrastructure, but it has not been modeled in the remote field devices on the transmission or distribution lines and has been only modeled for static use-cases that are integrated behind the head-end system in the data center, such as in Figure 2-7, or as a model transformation from IEC 61850 that reside within the boundary of a substation. As for the common semantic model standard, IEC 61850, it has shown to demonstrate interoperability between traditional substation automation and protection assets in Local Area Network (LAN) applications with high-speed, broadband communications, but not with distributed energy resources, such as solar inverters or energy storage. IEC 61850 also has been proven to have been successfully mapped to a pub/sub middleware, DDS, and its Interface Description Language (IDL) in a European utility application, but its models lacked vocabulary breadth outside the substation environment and also ease in bridging with other substations. Incidentally, there were research efforts in integrating substation assets to the central control center by employing CIM to address IEC 61850's vocabulary shortcomings, but they could not support the evolving and dynamic domains, such distributed energy resources. Furthermore, the harmonization efforts between IEC 61850 and CIM have also presented challenges and complexity due to IEC 61850's lack of extensibility and flat data structures, which are core traits of CIM.

As illustrated in Table 2-3, the various topics reviewed in the literature review by themselves can only partially satisfy the identified features needed to ensure sustainable interoperability of the electric grid that must support both static and dynamic functions in a hybrid centralized and distributed operations system, consisting of devices both inside and outside the data center or substation. Additionally, these interoperability features, listed in Table 2-3 on the next page, were also chosen in effort to alleviate and accelerate the grid's adoption of new dynamic technologies, such as intermittent renewables and unpredictable electric vehicle loads, where mission-critical operational decisions can be made inside a remote device that have the capability to exchange peer-to-peer data between any device or system, without relying on head-end systems for the field communication interfaces, as shown in Figure 2-9. Lastly, the proposed research framework is able to leverage all of the advantages and benefits of CIM, DDS and MQTT, while improving the ease of use of the implementation process.

Table 2-3: Summary of Literature Review Gaps Versus Proposed Research Framework

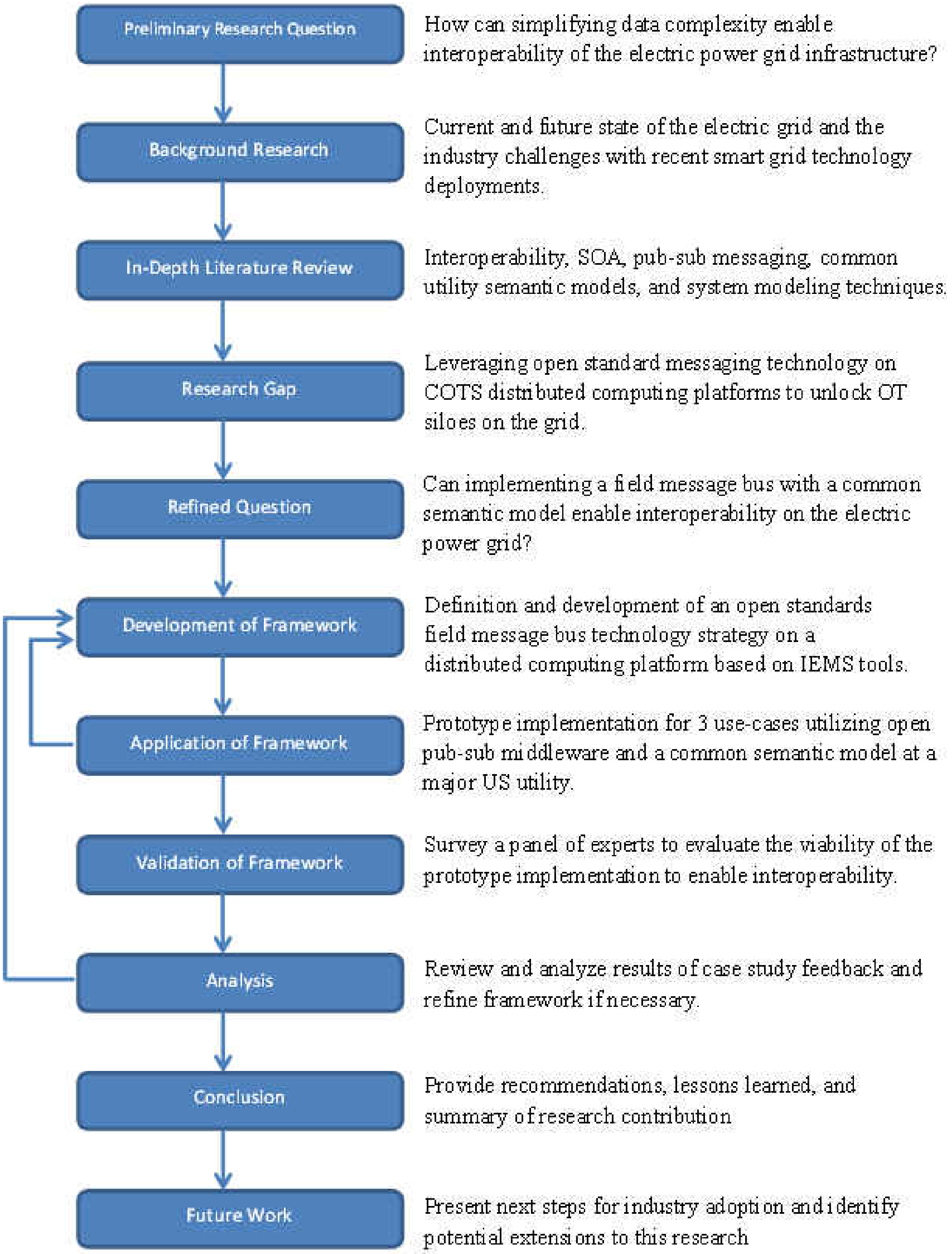
Interoperability Features	**SOA MOM**				**Utility Standard Semantic Models**		**Proposed Research Framework**
	Client/ Server	**Pub/Sub Messaging**			**IEC CIM**	**IEC 61850**	
	ESB	**MQTT**	**AMQP**	**DDS**			
US utility industry	X				X	X	X
Other industries	X	X	X	X			X
Ease of Use	X	X					X
Centralized data management	X	X	X		X		X
Distributed data management		X		X		X	X
Scalable			X	X			X
Enterprise Server hardware support	X	X	X	X			X
COTS embedded hardware support		X		X			X
Determinism				X			X
Fault-tolerance			X	X			X
Open Standard Protocol		X	X	X			X
Standardized API				X			X
Abstracted information model					X	X	X
Semantic contextual model				X			X
Syntactic Interoperability	X	X	X	X			X
Dynamic model support			X	X			X
Static model support	X	X	X	X	X	X	X
Extensible	X		X	X	X		X
Flat data structures					X		X
Rich vocabulary					X		X

CHAPTER 3: METHODOLOGY

This chapter provides the research methodology employed in this study that aims to enable interoperability in the electric utility industry. Due to the broad scope and steep learning curve required to understand the complex nature of the existing and future states of the electric grid technology, organizational, and political environments, a comprehensive background research and literature review were conducted in order to uncover a viable research gap that could be feasibly addressed by a practical development framework. Upon validation of its case study implementation, this novel framework can provide a quick starting point and reference architecture for others to continue and expand upon with the possibility of becoming commercial reality.

3.1 Research Methodology

The flow chart, in Figure 3-1, exhibits the process involved in the research methodology for this dissertation. Starting with the preliminary research question on how simplifying data complexity can enable interoperability in the electric grid infrastructure, an extensive background research and literature review were also pre-requisites to determine the challenges faced with the new smart grid technologies and their current shortcomings with interoperability and common semantic models that fail to unlock the value of the siloed information necessary to fully realize the benefits of today's existing smart grid infrastructure and information systems and tomorrow's future technology investments.



How can simplifying data complexity enable interoperability of the electric power grid infrastructure?

Current and future state of the electric grid and the industry challenges with recent smart grid technology deployments.

Interoperability, SOA, pub-sub messaging, common utility semantic models, and system modeling techniques.

Leveraging open standard messaging technology on COTS distributed computing platforms to unlock OT siloes on the grid.

Can implementing a field message bus with a common semantic model enable interoperability on the electric power grid?

Definition and development of an open standards field message bus technology strategy on a distributed computing platform based on IEMS tools.

Prototype implementation for 3 use-cases utilizing open pub-sub middleware and a common semantic model at a major US utility.

Survey a panel of experts to evaluate the viability of the prototype implementation to enable interoperability.

Review and analyze results of case study feedback and refine framework if necessary.

Provide recommendations, lessons learned, and summary of research contribution

Present next steps for industry adoption and identify potential extensions to this research

Figure 3-1: Flow Chart of Research Methodology

Once the research gap was clearly exposed and narrowed down in scope, a refined question could be formulated to trigger the need for developing of a framework that could be applied in a practical case study at a major utility and validated by survey of a panel of experts. After the analysis results support the framework objectives and satisfy the research gap, a summary of the overall research contribution along with the lessons learned and recommendations for next steps to facilitate a feasibility commercialization and successful industry adoption will be presented. The remaining sections of this chapter will highlight the major milestones identified in the methodology flow chart.

3.2 Preliminary Research Question

From the beginning of my research, the initial overarching goal of understanding how to deliver sustainable interoperability in the electric utility industry still remains the same. However, this scope was too wide at first and needed some boundaries to zoom into a distinct target and direction for the background research and literature review processes to follow. As a result, the initial question was centered around the idea of whether simplifying data complexity could enable interoperability of the electric power grid infrastructure.

3.3 Background Research and Literature Review

The background research for this topic entailed both theory in the academic journals and practical experience on the job as a smart grid technology development manager at both a large global utility OEM and one of the largest investor-owned utilities (IOUs) in the US. The academic theory included my industrial engineering curriculum, case studies, journal articles, novels, and simulation tools. The practical knowledge that led to a subject matter experience in smart grid technologies was obtained through the numerous technology evaluation projects on the job that involved extensive systems engineering development, significant interaction with many stakeholders in the utility organizations and vendor community, exposure to new emerging technologies considering entrance into the utility sector, and active attendance and participation at conferences, webinars, and roadshows. The subject matter expertise in the electric grid technology development helped paint the picture of the current state of the grid and its main challenges that are preventing the interoperability needed to support the future grid requirements that require situational awareness, modularity, and scalability. The academic theory helped provide me the systems engineering skillset, engineering management tools, and project management techniques to effectively define the root of the interoperability problem and to position my research for a novel contribution.

The literature review composed of primarily industry white papers, academic journal articles, and utility research institutional reports. Since the topics of interoperability and message-oriented middleware (MOM) are not well understood in the utility industry, extensive research was obtained from other high-tech industries that have better delineated the definitions and methods of interoperability, while also revealing benefits of the publish-subscribe (pub/sub) MOM in their commercial implementations. Since none of the other industries can closely match the physical, economic, and political environment of the electric utility sector, the literature review focused on identifying several key strengths and capabilities of potential applicable technologies that, when assembled together in the appropriate combinations and permutations, show promise for addressing the preliminary research question.

3.4 Research Gap and Refined Question

Given that the apparent challenges the utilities face with managing data complexity and delivering interoperability, there are many apparent gaps that could have be exposed by the background research and literature review. However, in order to expose the importance of interoperability, a simple and bold gap was identified and questioned to set a clear vision for simplifying the fundamental data complexity problem. After researching the lessons learned and potential capabilities in other commercial industries that have effectively solved interoperability, the clear research gap uncovered in this literature review is the lack of a framework to leverage open-standard pub-sub messaging middleware technology in conjunction with a common semantic model on COTS distributed computing platforms for demonstrating interoperability of electric grid assets, outside of the data center. With this recognized gap, the overall research question was refined to encompass whether implementing a field message bus strategy with a common semantic model can enable interoperability on the electric power grid.

3.5 Development of Framework

In order to deliver the framework required to fill the research gap for this dissertation, a development strategy that includes several different system engineering methods was considered. The first phase of the framework entailed applying the Matrix of Change (MOC) technique, which compares practices between current and future states of the electric grid, for both organizational and technological perspectives. The ensuing phase of the development framework, consisted of two steps that expanded upon the results of the MOC analysis by devising a strategy map and balanced scorecard for implementing interoperability at an electric utility organization. The next phase of this development process utilized the byproducts of the prior steps to create a reference architecture that defines the technical requirements for the overall electric grid distributed computing platform that employs the field message bus technology and common semantic model. Lastly, the final step of the framework proposed methodology for modeling use-cases with a common semantic model (i.e. CIM) and mapping their context to a pub/sub messaging middleware schema (i.e. DDS's IDL).

3.6 Application of Framework

Once the framework had been developed, the appropriate next step was to implement it in a practical case study. The case study was implemented and demonstrated at a major utility, Duke Energy, which modeled three different use-cases using a common semantic model, with structure similar to IEC CIM, for devices that will reside on the electric grid and are expected to communicate peer-to-peer and exchange information, outside the datacenter, on a common field message bus that employs the broker-less, extensible, and open standard, pub-sub protocol, DDS. The three electric grid use-cases that were modeled and simulated on a DDS field message bus were microgrid solar smoothing, inverter-island detection, and fault, location, isolation, sectionalization and restoration (FLISR), which include objects, such as a meter, recloser, phasor measurement unit (PMU), DMS, circuit breaker, and a distributed energy resource (DER) inverter for solar photovoltaic (PV) and battery storage systems. Lastly, the process of developing, modeling, testing, and simulating the common semantic model-defined assets on a field message bus on the electric grid was documented and demonstrated as a prototype prior to the validation of the framework in order provide a baseline level of background information on the research project to the panel of utility industry experts that are expected to be participate in the survey.

3.7 Validation and Analysis of Framework

Since the expected end-result of implementing this new field message bus technology is to increase sense of urgency for interoperability on the electric grid and drive the adoption of a common semantic model in the electric utility industry, an appropriate way to validate this framework is by administering a survey to a panel of experts. This panel will consist of subject matter experts that span the domains of the electric utility industry, IT, and standards organizations with backgrounds in power grid systems, IT enterprise integration, and data modeling.

The results of the survey from a panel of experts were analyzed to confirm the framework's feasibility and also provide input into the future work section. In addition to the documenting the survey process and results, the lessons learned of this experimental design were provided.

3.8 Conclusion and Future Work

As this work provides a reference framework to enable interoperability on the electric grid infrastructure, the summary of this research contribution is intended to be a starting point for others to expand upon. When the concept of translating and contextualizing information on the grid for distributed interoperable data exchange and faster local decisions is viewed favorable by utility stakeholders, the hope is that industry-wide partnerships can actively collaborate to define, mandate, certify, update, and manage the semantic models of the major objects and operational functions that make up the future state of the electric grid.

CHAPTER 4: DEVELOPMENT OF FRAMEWORK

This chapter documents the development process of the proposed research framework that was designed to facilitate interoperability in the US electric grid infrastructure. This section includes a basic process overview, a series of engineering management analysis techniques, a reference architecture definition, and an use-case application framework in effort to help model, simulate, and verify the interoperability capability of an operational system function on the electric grid.

4.1 Proposed Framework Overview

The proposed interoperability framework, illustrated in Figure 4-1, was split up into five major steps: the Matrix of Change (MOC), strategy map, balanced scorecard, reference architecture, and use-case application framework. The first three steps, which exploited engineering management capstone techniques, were conducted sequentially and lean more heavily toward a business and organizational strategy. The final two steps, which are a sheer collection of architectural requirements, were also conducted in series, but were geared more toward a technological strategy. As a result, the MOC tool in step one, which analyzes both the organizational and technological states of the US electric utility industry when influenced by interoperability, is a functional prerequisite for both the strategy map in step two and technical reference architecture in step four.

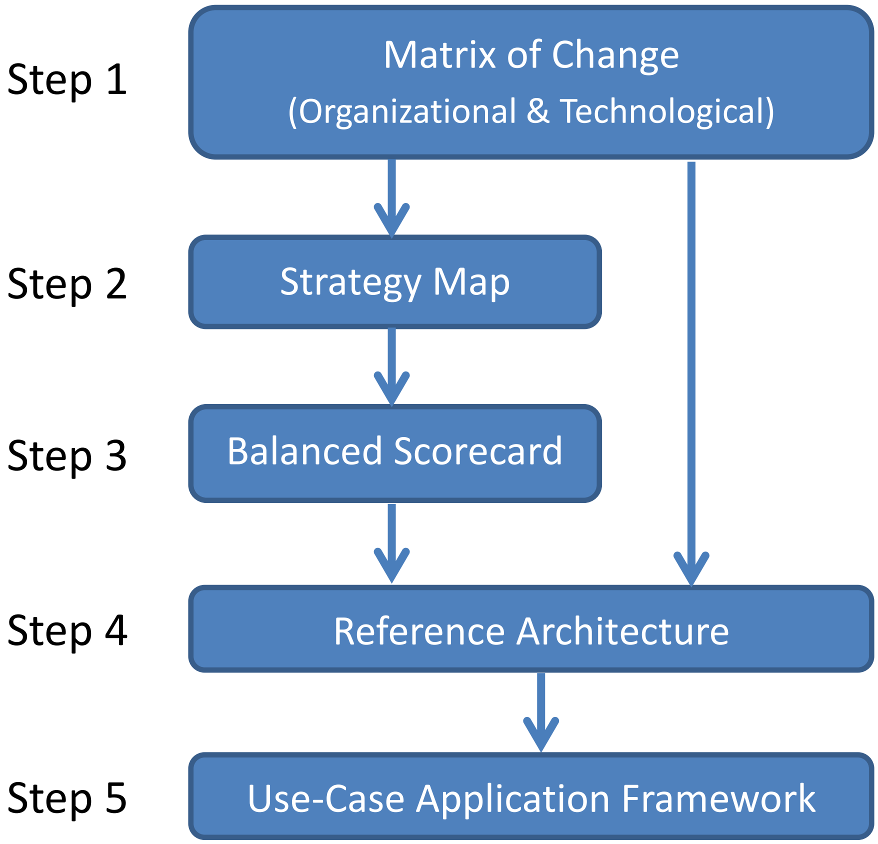


Figure 4-1: Development Process for the Proposed Interoperability Framework

4.2 Matrix of Change Analysis

The Matrix of Change (MOC) was the first engineering management tool utilized in the development process for this interoperability framework (Brynjolfsson, Renshaw, & Van Alstyne, 2007). Developed as a joint research project by the Massachusetts Institute of Technology (MIT) Center of Coordination Science and the Center for eBusiness@MIT, the MOC is an IT-enabled change management tool to facilitate the visualization of existing and desired states of a proposed organizational or technological change, as well as the complementary or conflicting interactions that impact not only the complexity, difficulty, and stability of the re-engineered system processes, but also influence the strategy for determining the timing, pace, and sequence of the execution, the location and environment of the implementation, and the degree of coordination among stakeholders during the transition (MIT, n.d.).

As depicted in Figure 4-2, the MOC is comprised of three different matrices:

- Horizontal matrix: represents current or existing processes and practices
- Vertical matrix: represent target or desired processes and behavior
- Transition matrix: represents the bridge connecting horizontal and vertical

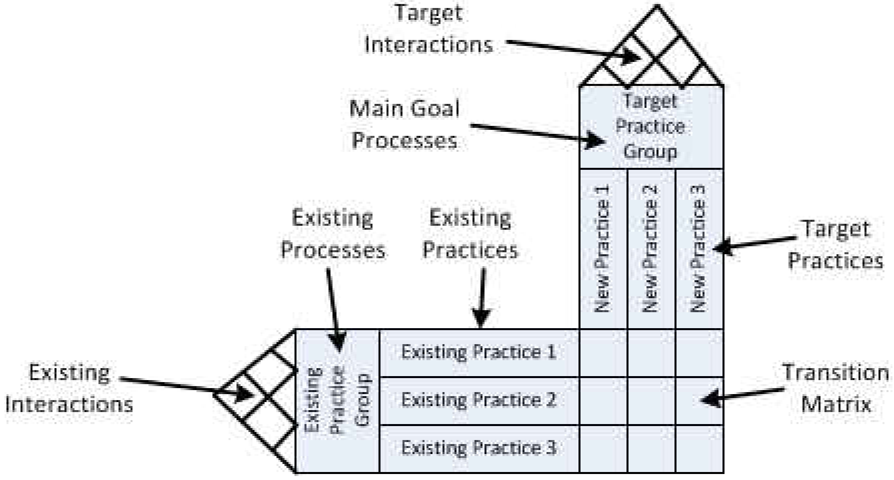


Figure 4-2: Major Components of the MOC (adapted from MIT, n.d.)

Within each MOC matrix, there are three types of interactions:

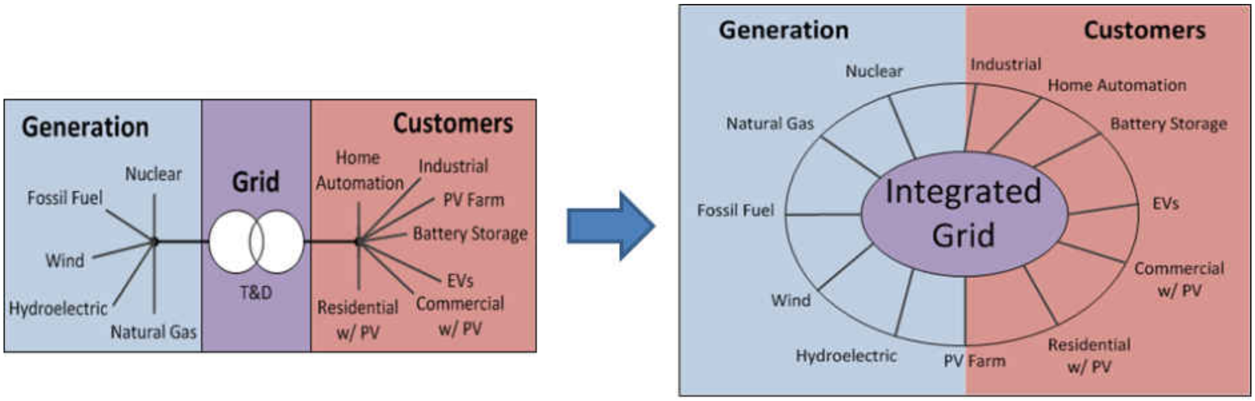
- Reinforcing: signified by “+” sign,
- Interfering: signified by “-“ sign
- Neutral: signified by no sign

The horizontal matrix, in Figure 4-2, characterizes the current critical processes, also known as existing practice groups, which include a distinct set of existing practices that are each compared with one another to determine the relationship between each existing practice interaction, whether reinforcing, interfering, or neutral (Brynjolfsson et al., 2007) The vertical matrix describes the main goal processes in the future, also known as target alternative practices, which include a discrete set of new practices that are also compared with one another to determine the relationship between each target practice interaction, whether reinforcing, interfering, or neutral (2007). The transition matrix compares the relationship between the current existing practices and new target practices and identifies the various complementary and opposing interactions between them (2007). In general, a high presence of conflicting interactions between the two states indicates a potentially challenging transition strategy, while a highly complementary transition matrix exemplifies a less difficult and less disruptive system transformation.

The MOC tool has been utilized and performed for transportation logistics, manufacturing supply chain, and healthcare applications, but has not been applied to the electric utility sector prior to this research (Brynjolfsson et al., 2007; MIT, n.d.). Due to the risk-adverse and change-resistant nature of stakeholders in the electric utility industry, the introduction of new technology was deliberately utilized as a catalyst to simplify the change management for the electric grid operations. As a result, two separate MOC approaches were developed: one for a top-down organizational perspective and the other for a bottoms-up technological viewpoint.

4.2.1 Organizational Perspective

The organization perspective analyzes the business implications of the current state of the electric grid and the impact of interoperability on the future state of the electric grid as described in the introduction section. As illustrated in Figure 4-3, the existing processes are characterized by the five goals in the current state mission and the target processes are characterized by seven goals in the future state mission.



Current State Mission:

1. **Safe**
2. **Reliable**
3. **Affordable**
4. **Environmentally Responsible**
5. **Connected**

Future State Mission:

1. **Safe**
2. **Reliable**
3. **Affordable**
4. **Environmentally Responsible**
5. **Integrated**
6. **Resilient**
7. **Flexible**

Figure 4-3: Current vs Future State of US Electric Grid (adapted from Brooks 2014; EPRI 2014)

4.2.1.1 Current Organizational Practices

As depicted in Figure 4-3, the current state of the US electric grid involves organizational processes centered around managing and operating its power infrastructure in a way that is safe, reliable, affordable, environmentally responsible, and connected. As shown in Figure 4-4, there are multiple existing practices that characterize each existing process in the current state's mission. In addition, highly complementary interactions between the safe, reliable, and affordable categories are evident, while a noticeable amount of reinforcing behavior is apparent between the environmentally responsible and connected groupings with reliable and affordable.

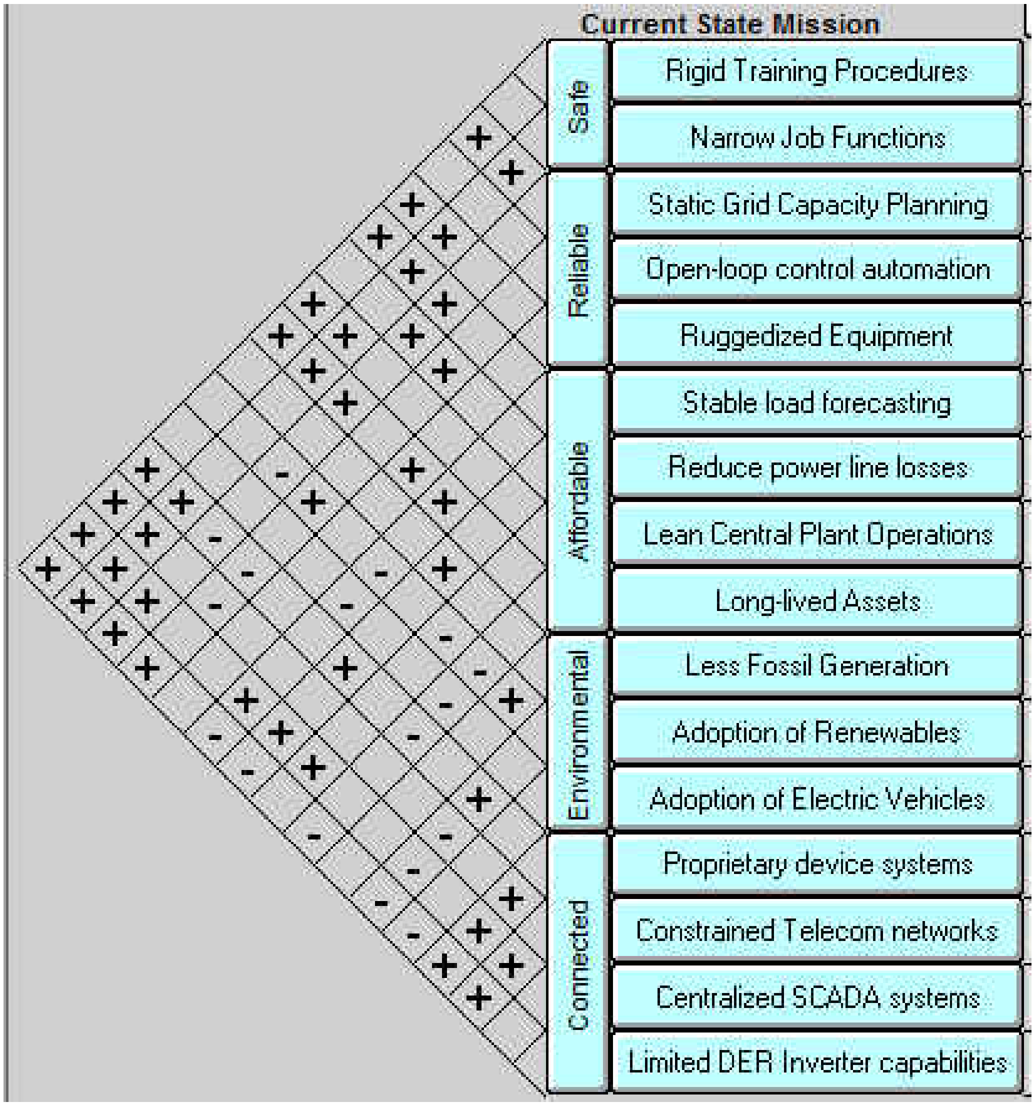


Figure 4-4: Existing Practices for the Organizational Matrix of Change Tool

In reviewing the various current practices from the horizontal matrix in Figure 4-4, the rigid training procedures and narrow job functions have worked well for a long time to ensure a safe electric grid operations. The practice of planning the capacity of the power delivery operations as a static system, deployment of open-loop automated control solutions, and robust hardware requirements for outdoor ruggedized equipment has helped harden the reliability of the grid. The predictable forecasts of stable load consumption, the power delivery efficiency gains from reduced line losses, the lean central plant operations, and the long life expectancies of the assets that can last between 30-50 years, have each contributed to making energy costs fairly affordable. The sustainability efforts to reduce fossil generation, increase the adoption of renewables, and embrace the electric vehicle adoption, have all been driven by the sense of the urgency to become the environmentally responsible. The recent smart grid efforts of adding proprietary metering, sensor, and device solutions, adopting constrained private telecom networks, enhancing centralized SCADA systems, and employing today's distributed energy resource (DER) inverter technologies that can only offer limited functionality, are the most common ongoing technologies that electric utilities have invested into in order to better connect devices and systems to the grid.

In summary, of the various existing practices, the connected mission practices, which were mainly instilled as a result of striving to be more environmentally friendly, have mostly interfered with the current practices for safe, reliable, and affordable categories, which essentially can help motivate organizational change to occur as the penetration levels of DERs and digital devices increase.

4.2.1.2 Target Organizational Practices

As displayed in Figure 4-3, the future state of the US electric grid has a target mission to be safe, reliable, affordable, environmental, integrated, resilient, and flexible. In examining the vertical matrix in Figure 4-5, zero touch configuration and refining the technical skillsets of the field workforce are the goals for enhanced safety. The practice of optimizing power quality, performing condition-based monitoring, enabling accurate situational awareness from an electrical connectivity perspective, and providing distribution line voltage and volt-amp reactive (Var) support from distributed generators, are all potential ways to help improve the reliability of the future electric grid. The target initiatives to strive for modular components, multi-functional devices, multi-source supply chain choices, faster product and system deployments cycles, capital infrastructure deferment alternatives, and fewer obsolete systems, are all likely scenarios to help make the energy costs more affordable. The sustainability efforts to encourage use of in-premise automation technologies (i.e. smart thermostats, LED lighting, and smart appliances), embrace a higher penetration rate of renewables, implement continuous emissions monitoring and optimal control of SOx, and NOx, and expand its electric vehicle infrastructure, are each future prospective activities to address being environmentally responsible. From a technology perspective, the target initiatives of implementing simpler visualization tools of remote assets, a hybrid system of distributed and centralized architecture, standardized communication and application protocol interfaces, and common semantic data models, are all potential methods of delivering a fully integrated grid system that is both connected and interoperable.

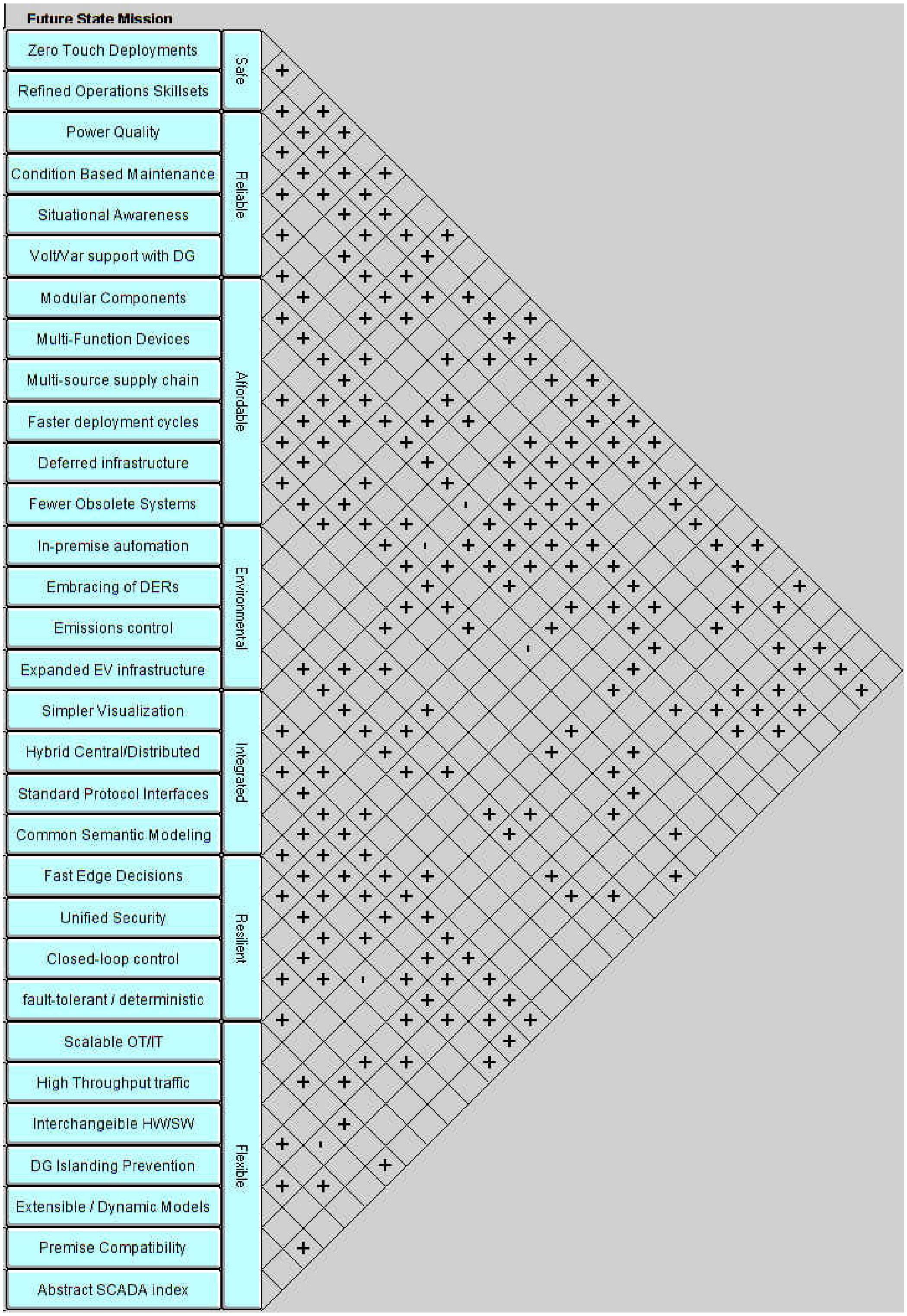


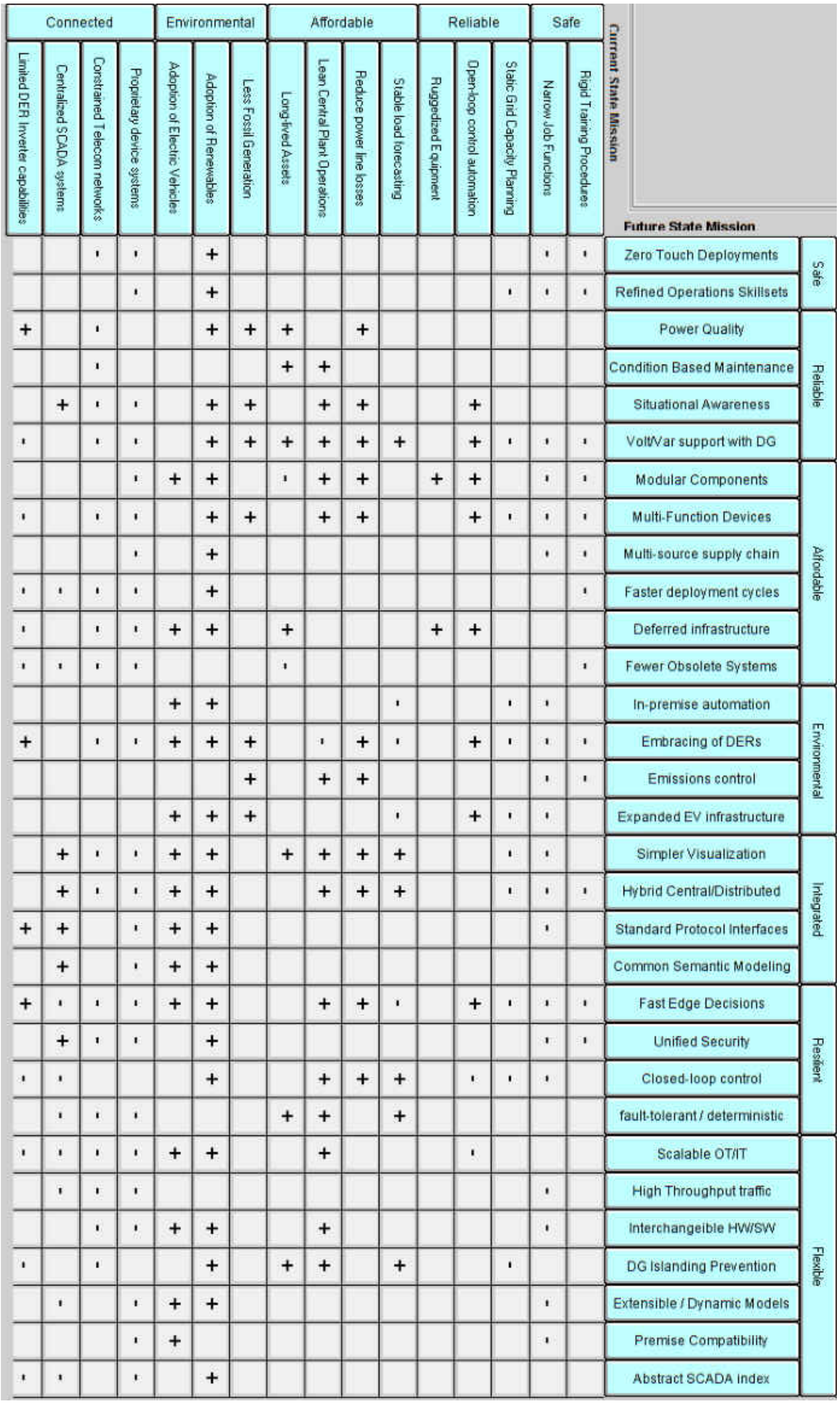
Figure 4-5: Target Practices for the Organizational Matrix of Change Tool

As a byproduct of delivering a plug-and-play integrated electric grid infrastructure, the new practices of devices allowing for fast edge decisions, containing a unified security platform, employing distributed closed-loop control schemes, and enabling fault-tolerant and deterministic systems behavior, are all future capabilities to improve the resiliency of the electric grid. In addition, another byproduct of integrated grid interoperability is the enhanced flexibility feature, which is accomplished by attaining a scalable OT/IT data infrastructure, supporting high-throughput communication data traffic, embracing interchangeable hardware and software components, preventing distributed generation islanding phenomena, allowing for the extensibility of data models to be conducted dynamically, positioning the grid infrastructure to be compatible and interoperable with in-premise automation devices in the future, and abstracting and reducing the number of distributed SCADA end-points that reside in the centralized master index list in the back-office data center.

In summary, the various identified new target practices, in Figure 4-5, have mostly highly complementary behavior with each other as demonstrated by the safe, reliable, environmental, and integrated categories showing no conflicting relationships. Of the categories that do exhibit a few interfering relationships, such as affordable, resilient, and flexible, the interactions are minor as they relate to an expanded electric vehicle infrastructure, simpler visualization tools, unified security, and high-throughput data traffic, which can all be overcome by leveraging the benefits of the other complementary interactions within each target mission or practice group.

4.2.1.3 Organizational Transition Matrix

During the investigation of the transition matrix in Figure 4-6, the intersection of the existing and target practices produces a mix of complementary and interfering interactions between the two. First, when comparing the existing safe practices in the current state versus the future states, it is very evident there exists a large opposing forces between them, which signifies a challenging obstacle that will need to be addressed in the balanced scorecard and be overcome by the highly complementary interactions between the other existing and target practices. Next, when comparing the static planning process of power delivery capacity, which resides in the existing reliable mission practice group, to the other target processes, it is also clear that these heavy conflicting interactions need special attention during the organizational transition strategy. Fortunately, the existing affordable and environmentally responsible practices in the current state of the electric grid do exemplify strongly complementary behavior with other target practice categories, which could be utilized as an instrument to drive internal change on the safety and operational planning functions. Lastly, when comparing the existing practices in the connected category group versus the other target practices, there exists many interfering interactions, but can be resolved by taking advantage and influencing the interoperability requirements of the new disruptive technologies being introduced, such as distributed energy resources, electric vehicles, and in-premise automation, in response to the external market’s demand for highly complementary environmentally-responsible mission.



Connected				Environmental			Affordable				Reliable			Safe		Current State Mission	
Limited DER Inverter capabilities	Centralized SCADA systems	Constrained Telecom networks	Proprietary device systems	Adoption of Electric Vehicles	Adoption of Renewables	Less Fossil Generation	Long-lived Assets	Lean Central Plant Operations	Reduce power line losses	Stable load forecasting	Ruggedized Equipment	Open-loop control automation	Static Grid Capacity Planning	Narrow Job Functions	Rigid Training Procedures	Future State Mission	
		'	'		+									'	'	Zero Touch Deployments	Safe
			'		+								'	'	'	Refined Operations Skillsets	
+		'			+	+	+		+							Power Quality	Reliable
		'					+	+								Condition Based Maintenance	
	+	'	'		+	+		+	+			+				Situational Awareness	
'		'	'		+	+	+	+	+	+		+	'	'	'	Volt/Var support with DG	
			'	+	+		'	+	+		+	+		'	'	Modular Components	Affordable
'		'	'		+	+		+	+			+	'	'	'	Multi-Function Devices	
			'		+									'	'	Multi-source supply chain	
'	'	'	'		+										'	Faster deployment cycles	
'		'	'	+	+		+				+	+				Deferred infrastructure	
'	'	'	'				'								'	Fewer Obsolete Systems	
				+	+					'			'	'		In-premise automation	Environmental
+		'	'	+	+	+		'	+	'		+	'	'	'	Embracing of DERs	
						+		+	+					'	'	Emissions control	
				+	+	+				'		+	'	'		Expanded EV infrastructure	
	+	'	'	+	+		+	+	+	+			'	'		Simpler Visualization	Integrated
	+	'	'	+	+			+	+	+			'	'	'	Hybrid Central/Distributed	
+	+		'	+	+									'		Standard Protocol Interfaces	
	+		'	+	+											Common Semantic Modeling	
+	'	'	'	+	+			+	+	'		+	'	'	'	Fast Edge Decisions	Resilient
	+	'	'		+									'	'	Unified Security	
'	'				+			+	+	+		'	'	'		Closed-loop control	
	'	'	'				+	+		+						fault-tolerant / deterministic	
'	'	'	'	+	+			+				'				Scalable OT/IT	Flexible
	'	'	'											'		High Throughput traffic	
		'	'	+	+			+						'		Interchangeible HW/SW	
'		'			+		+	+		+			'			DG Islanding Prevention	
	'		'	+	+									'		Extensible / Dynamic Models	
			'	+										'		Premise Compatibility	
'	'		'		+											Abstract SCADA index	

Figure 4-6: Transition Matrix for the Organizational Matrix of Change Tool

4.2.2 Technological Perspective

The technological perspective analyzes the technology implications of the current information exchange process in today's operational infrastructure, known as polling of data, versus the future technological state, which employs publish-subscribe (pub/sub) messaging to enable data exchange interoperability in tomorrow's operational infrastructure. As a result, both existing and target processes, of the current and future technological states, respectively, are characterized by four of practice groups with three of them, namely the data integration, reliability, and scalability categories, being the same ones in each the current and future technological states. As for the only category difference between the two matrices, the current state is characterized by polling data, while future state is described by exchanging data via pub/sub messages.

4.2.2.1 Current Technological Practices

In reviewing the various current practices from the horizontal matrix in Figure 4-7, the process of employing a centralized polling data IT architecture yields unfiltered data streams, bypass-routed traffic known as "pass-through," slow response times and high-latency decisions, binary messages known as "points" or text strings, and heavy messages that are typically network constrained. As for the data integration category, the current state entails proprietary and rigid data structures, application interfaces that are tightly coupled to business logic, hierarchical data models that are mapped only in the back-office data center, and modeling behavior that is traditionally static in nature. As for the data reliability group, the current IT message protocols utilized have error-prone code due to the custom and immature nature of it, have inherently unreliability delivery behavior even with transmission control protocol (TCP) and internet protocol (IP), and are a single-point of failure given the client/server, master/slave, or broker-based middleware paradigm selections in the back-office. Lastly, for the scalability group, the current state of polling necessitates unicast transmission capability, the support of multiple disparate element managers for each proprietary device system, a saturated centralized SCADA master index "points" list in the data center, and a limited overall system throughput of around a million messages per minute.

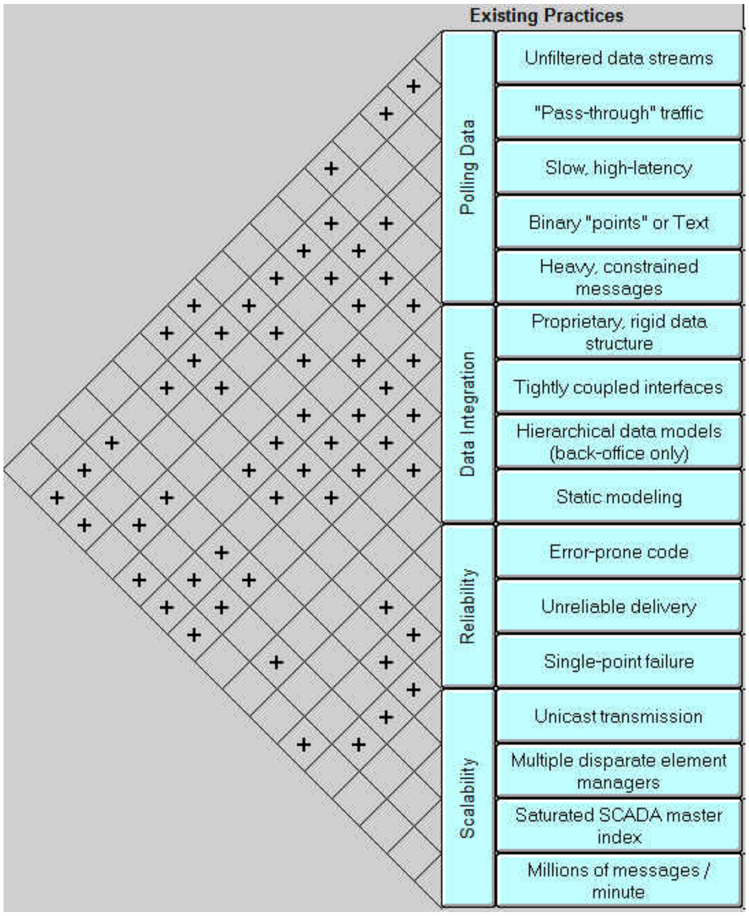


Figure 4-7: Existing Practices for the Technological Matrix of Change Tool

In summary, since the interactions between the existing practices are highly complementary with no conflicting interactions, a change to future state that can solve many of the existing shortcomings should make the transition fairly seamless, especially if the new data sharing architecture can innocuously augment and support the existing data exchange processes of polling in parallel to its technological improvements.

4.2.2.2 Target Technological Practices

In identifying the various target practices from the vertical matrix in Figure 4-8, the process of utilizing a distributed and broker-less pub/sub IT architecture enables the ability for filtered and prioritized data traffic, local processing and storage, fast response times and low-latency decisions, binary messages as waveforms and events, and lightweight messages that can be compressed for efficient networking. As for the data integration category, the target state facilitates common semantic data structures, open and standardized message bus protocol Application Protocol Interfaces (APIs), flattened data models that can be mapped both in the FAN and back-office, and modeling behavior that can be extended dynamically. As for the data reliability group, the new pub/sub paradigm employs mature and off-the-shelf software with limited coding errors, deterministic behavior that can guarantee message delivery, and fault-tolerant failover ability that provides redundancy. For the scalability group, the future state of pub/sub necessitates multi-cast transmission, a single and unified visualization lens, abstracted and distributed system of systems, and a potential overall system throughput of over a billion of messages per second.

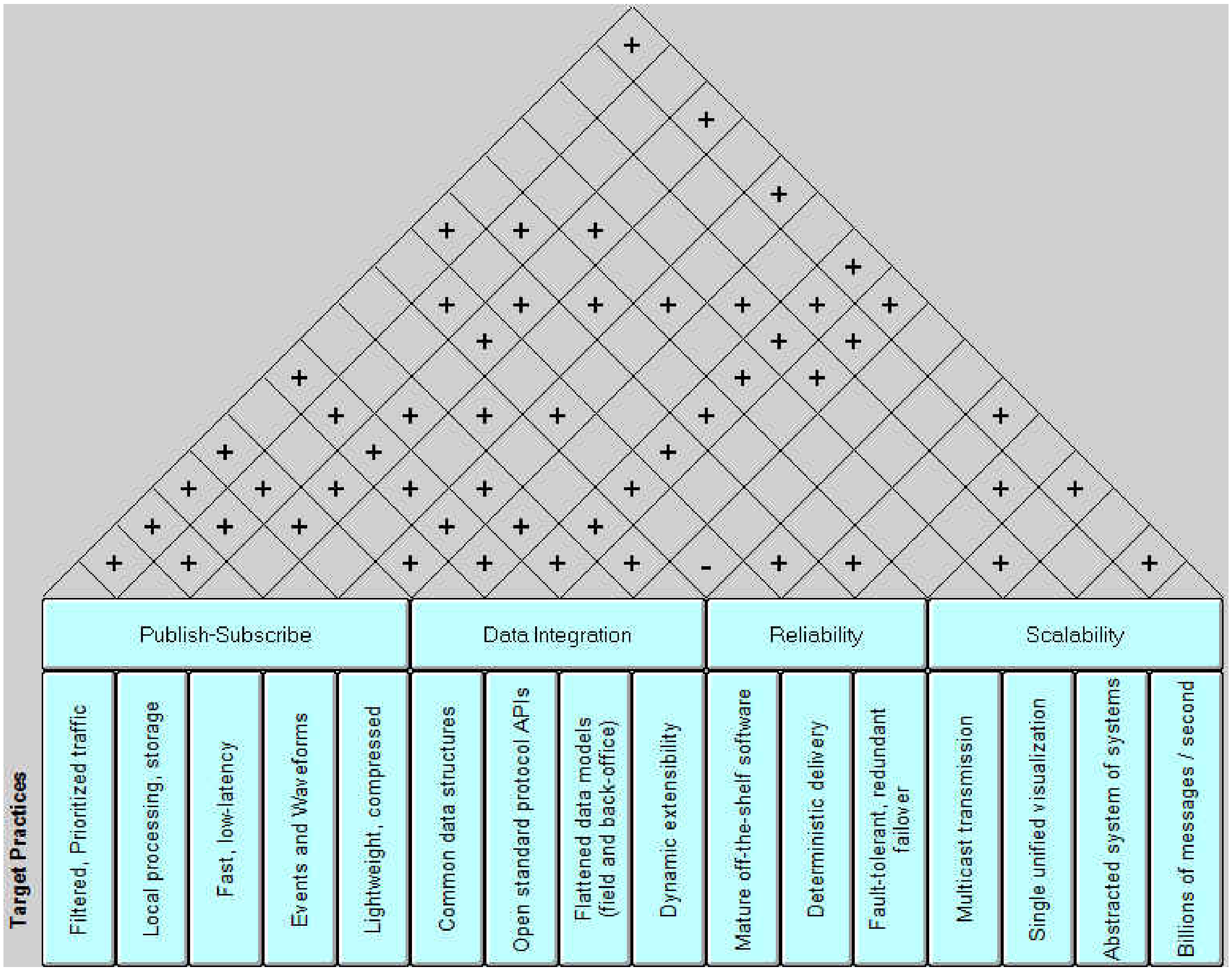
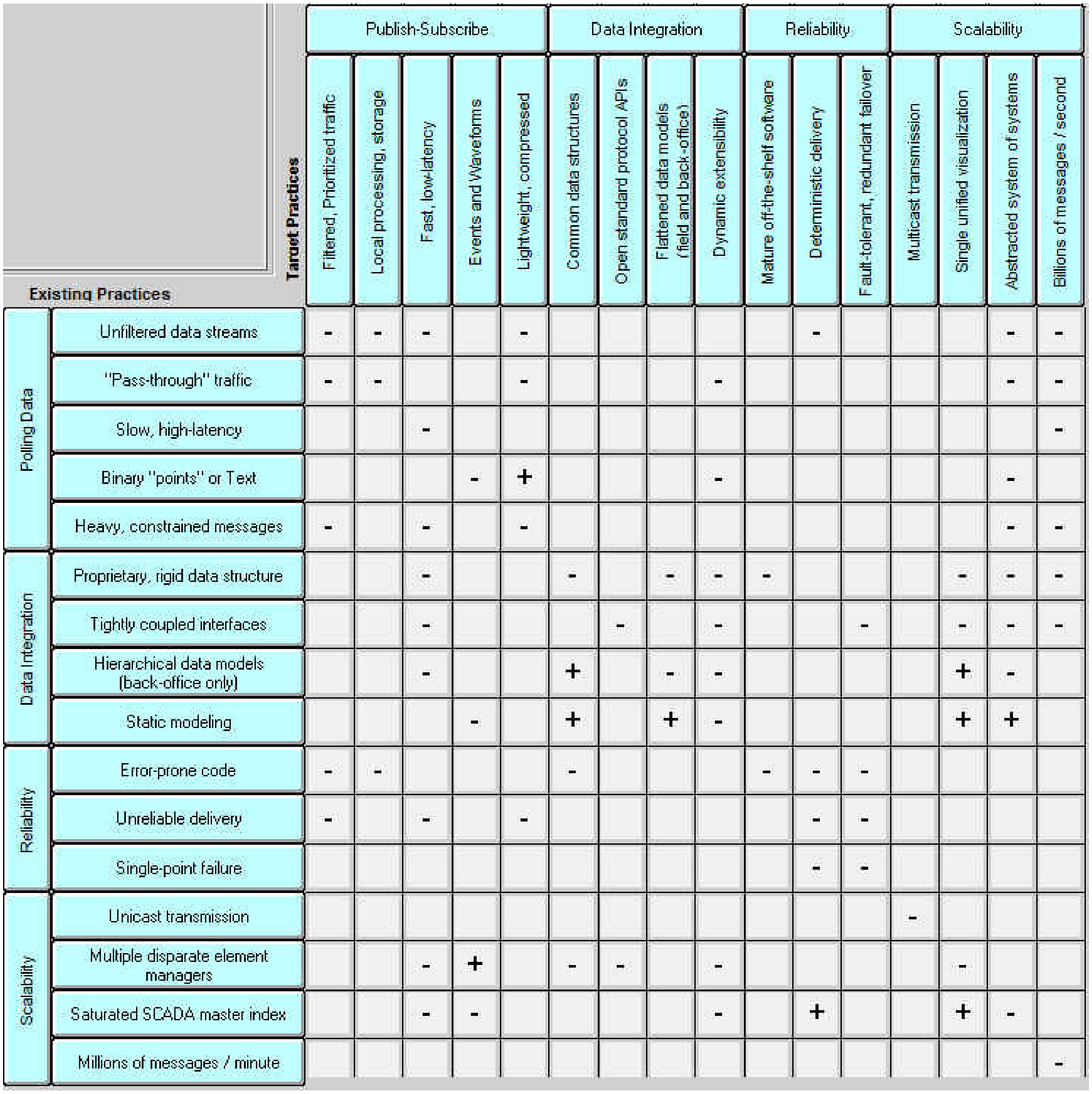


Figure 4-8: Target Practices for the Technological Matrix of Change Tool

In summary, the various identified new target practices from the vertical matrix, in Figure 4-8, exhibit mostly highly complementary behavior when compared with each other, with the minor exception of mature, off-the-shelf software interacted with dynamic extensibility. As a result of introducing pub/sub messaging technology to supplement the traditional data polling architecture, the new future technological state has the potential to provide cohesion and stability to the system, while also allowing for limited restrictions on timing, schedule, and location strategies.

4.2.2.3 Technological Transition Matrix

During the examination of the transition matrix in figure 4-9, the intersection of the existing and target practices produce highly interfering interactions between the two.



Existing Practices	Target Practices	Publish-Subscribe					Data Integration				Reliability			Scalability			
		Filtered, Prioritized traffic	Local processing, storage	Fast, low-latency	Events and Waveforms	Lightweight, compressed	Common data structures	Open standard protocol APIs	Flattened data models (field and back-office)	Dynamic extensibility	Mature off-the-shelf software	Deterministic delivery	Fault-tolerant, redundant failover	Multicast transmission	Single unified visualization	Abstracted system of systems	Billions of messages / second
Polling Data	Unfiltered data streams	-	-	-		-						-				-	-
	"Pass-through" traffic	-	-			-				-						-	-
	Slow, high-latency			-													-
	Binary "points" or Text				-	+				-						-	
	Heavy, constrained messages	-		-		-										-	-
Data Integration	Proprietary, rigid data structure			-			-		-	-	-				-	-	-
	Tightly coupled interfaces			-				-		-			-		-	-	-
	Hierarchical data models (back-office only)			-			+		-	-					+	-	
	Static modeling				-		+		+	-					+	+	
Reliability	Error-prone code	-	-				-				-	-	-				
	Unreliable delivery	-		-		-						-	-				
	Single-point failure											-	-				
Scalability	Unicast transmission													-			
	Multiple disparate element managers			-	+		-	-		-					-		
	Saturated SCADA master index			-	-					-		+			+	-	
	Millions of messages / minute																-

Figure 4-9: Transition Matrix for the Technological Matrix of Change Tool

Given the dominance of conflicting interactions, it is evident that the anticipated strategy of introducing the pub/sub messaging technology should be devised and implemented in a way that can concurrently and seamlessly retrofit existing polling systems without impacting the performance and function of the current legacy infrastructure. Therefore, a strong consideration for a new pub/sub technology middleware that is virtual, lightweight, portable, and compatible to the existing polling solutions will be desired. Lastly, when implemented successfully, these new target capabilities will not only help overcome the current technological shortcomings in data integration, reliability, and scalability, but also act as a catalyst to smoothen and expedite the transition period for the electric utility organizational changes that are needed to enable interoperability on the grid infrastructure.

4.3 Strategy Map

The second engineering management tool utilized in the development process for this interoperability framework was the strategy map, which is a logical visualization tool that explicitly describes the strategy's testable hypothesis by specifying the key overall objectives and customer value propositions, depicting the cause-and-effect linkages among stakeholders, external customers, internal business operations, and strategic competencies, and translating modern day technology-related processes with intangible knowledge-based assets into operational terms that can be associated with tangible financial end results (Kaplan & Norton, 2001). Moreover, since intangible assets in today's information age have the potential to generate indirect, contextual, and sustainable value that fuels competitive advantage, the strategy map is typically developed in a top-down manner that coordinates the measured financial outcomes with the targeted themes and objectives needed to effectively describe, understand, and execute an organization's desired goals (2001). Furthermore, the strategy map not only connects the internal innovation competences with the operational processes to create a differentiated customer value proposition, but it also provides the foundation to the balanced scorecard, which is a long-term strategic management measurement instrument (2001).

An adaptation of Kaplan and Norton's balance scorecard strategy map template is shown in Figure 4-10, which specifies the four main perspectives (p. 96, 2001):

- Financial: focused on shareholder value
    - Consisting of growth and productivity themes
- External: centered around adding context to customer value proposition
    - Consisting of themes for product leadership, customer intimacy, and operational excellence
- Internal: defines new business processes to support differentiated value
    - Consisting of innovation, customer management, operational, and regulatory processes.
- Learning & Growth: defines high-priority workforce activities
    - Consisting of competencies, technologies, and organizational climate

Within each perspective, there are several different types of strategic themes to choose from that complement the objectives selected and connected together in the strategy map. For example, as exhibited in Figure 4-10, the growth and productivity themes characterize the financial perspective, while product leadership, customer intimacy, and operational excellence epitomize the external perspective.

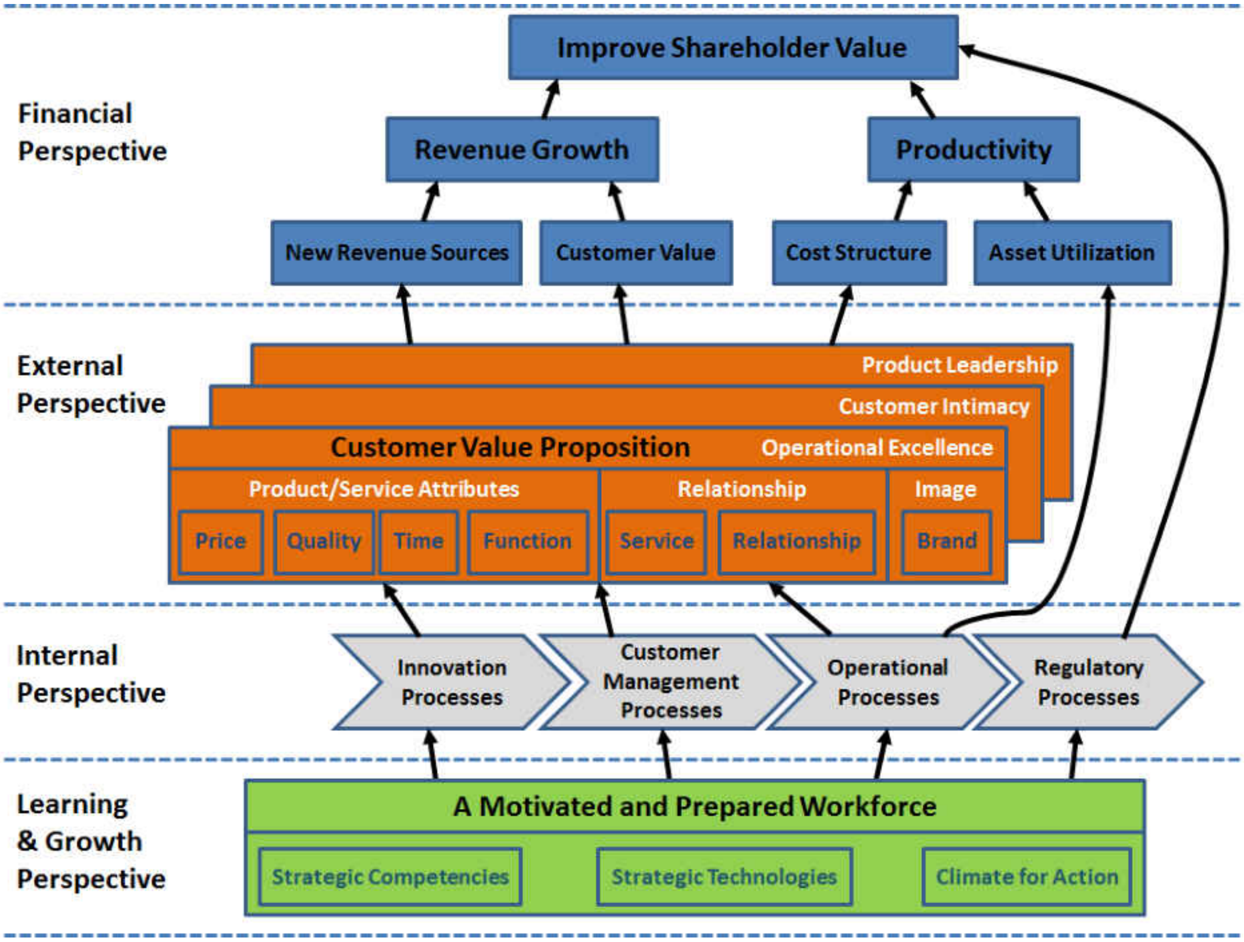


Figure 4-10: Adaptation of the Strategy Map Template (Kaplan et.al, 2001)

After considering the organizational obstacles and technology recommendations derived in the MOC step of this development process in section 4.2 and applying them to the template above in Figure 4-10, the following strategy map for the this interoperability framework was produced and illustrated in Figure 4-11.

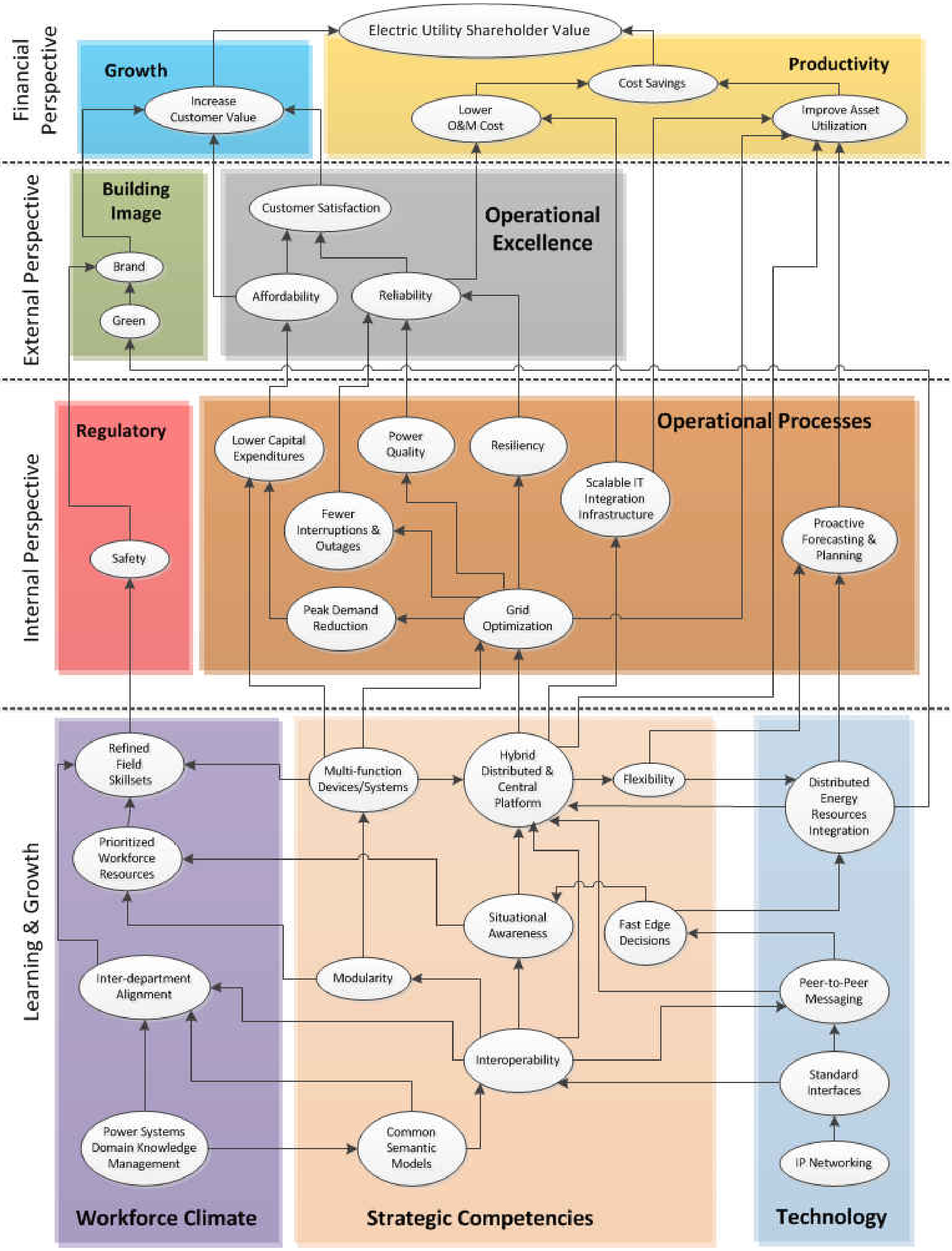


Figure 4-11: Strategy Map for Enabling Interoperability in the US Electric Grid

As exhibited in Figure 4-11, it is evident that revenue growth and productivity themes were employed for the financial perspective, building image and operational excellence were utilized for the external or customer perspective, regulatory and operational processes were exploited for the internal perspective, and workforce climate, strategic competencies, and technology were used for the learning and growth perspective. Additionally, it is apparent that the technologies and competencies at the bottom of the strategy map in the learning and growth section correspond to the areas of research in the literature review and the hypothesis to the tested in this dissertation.

With the overall goal of an electric utility to increase shareholder value, the target goals of increasing the customer value and generating cost savings were the primary financial drivers for this strategy map. In order to deliver growth in customer value, improvements in the brand image (via environment and safety), affordability (via decreased energy bills from lower capital expenditures), and customer satisfaction (via better affordability and reliability) are needed due to the regulatory environment of the US utility industry. With regard to productivity, lower operational & maintenance (O&M) costs and enhanced asset utilization are essential to deliver the direct and indirect cost savings in a timeframe that is much sooner than the customer value objective.

From the regulatory internal perspective, safety practices and procedures are improved with refined field workforce skillsets and inter-department alignment within the utility organizations. In regard to the operational processes of the internal perspective, fewer interruptions or outages, better power quality, and greater resiliency or faster restoration, all lead to better reliability as a result of grid optimization, which also reduces peak demand and more effectively utilizes assets. Other operational excellence objectives include the scalable IT integration infrastructure, which can improve bottom line via both lower O&M and better asset utilization, and the proactive forecasting and planning, which benefits asset utilization as a result of increased flexibility and introduction of seamless DER integration capabilities.

With regard to the strategic competencies theme within the learning and growth perspective, multi-function devices or systems reduce capital costs, enable grid optimization, and enhance the hybrid distributed and centralized platform, as a result of having modularity via interoperability. The hybrid distributed and centralized platform yields enhanced asset utilization, grid optimization, IT scalability, and flexibility, as a result of having capabilities such as situational awareness, interoperability, seamless DER integration, and peer-to-peer messaging. The competency of situational awareness is a result of interoperability and fast edge decisions, which are enabled by peer-to-peer messaging and is an enabling feature for DER integration. Interoperability, which is the most crucial strategic competency and heart of this strategy map, is a byproduct of mapping common semantic models (via power systems domain knowledge management) with appropriate standard interfaces (via internet protocol networking).

With regard to the other competencies in the learning and growth section, the technology of peer-to-peer messaging is enabled by both interoperability and standard interfaces, while in the workforce climate theme, the refined field skills are a result of multi-functional devices or systems and prioritized workforce resources, which is enhanced by situational awareness and modularity. Lastly, the strategic inter-department alignment within the workforce climate section is made possible with interoperability, simplified IT governance (via common semantic models), and power systems domain knowledge management.

4.4 Balanced Scorecard

The third engineering management tool utilized in the development process for this interoperability framework was the balanced scorecard, which is the fundamental next step and extension of the strategy map in order to incorporate tangible measurements to the various objectives and their cause-and-effect linkages (Kaplan et al, 2001). Since tangible and intangible assets can be bundled, the balanced scorecard includes quantitative measures, that are both financial and non-financial indicators, such as time, quantity, performance, surveys, and rates (2001). Upon successful completion of a strategy map and balanced scorecard, the strategy of an technology organization should be not only be translated into operational terms, but it should be clearly understood by the key stakeholders, so that the organization can be positioned to mobilize change through executive leadership, continually improve corporate and individual strategic awareness, and align the various corporate functions within the company to deliver synergies (2001) . Table 4-1 portrays the balanced scorecard approach for this interoperability framework in the US electric utility industry.

Table 4-1: Balanced Scorecard for Enabling Interoperability in the US Electric Grid

Perspective	**Themes**	**Objectives**	**Measures**
Financial	Growth	Customer Value	Revenue growth
			# of energy transactions and its average value
			Customer retention
	Productivity	Lower O&M	Lower O&M expenditures
		Asset Utilization	Efficiency of power generation and delivery assets
			Reduced overhead: labor, external services, infrastructure
		Cost Savings	All overhead and variable costs
External	Operational Excellence	Affordability	Energy bill
		Customer Satisfaction	Industry survey ranking (e.g. J.D. Power)
		Reliability	All reliability Indices: SAIFI, CAIFI, MAIFI, SAIDI, CAIDI
			# of service calls/dispatches
			Asset health indicators
	Building Image	Brand	Environmental friendliness; Fewer carbon emissions
			Safety indices
			Community engagement
Internal	Operational Processes	Fewer Interruptions/Outages	Frequency indices: SAIFI, CAIFI, MAIFI
		Resiliency/Faster Restoration	Duration indices: SAIDI, CAIDI
		Power Quality	Overall system frequency (Hz); Lower ancilliary services
			Power Factor (%): average performance near unity
			Total Harmonic Distortion (%)
		Peak Demand Reduction	Amount of Spinning Reserves
		Grid Optimization	Consistency & stability of power delivery
			Efficient power delivery: reduced power line losses
		Scalable IT infrastructure	Reduced IT integration effort for increased data
		Proactive Forecasting & Planning	Reduced demand forecast lead-times (sec)
			Faster overall system control decision response times (sec)
		Lower Capital Expenditures	Lower supply chain costs
			Deferred expansion
			Fewer redundant assets
	Regulatory	Safety	Fewer Accidents
Learning & Growth	Workforce Climate	Refined Field Skillsets	IT, Telecom skillset certifications for remote upgrades
		Prioritized Workforce Resources	Condition-based maintenance indices & fewer truck rolls
		Inter-department alignment	Faster deployment and execution time (min or days)
			Simplified IT data governance; fewer databases
			Cross-organization synergies: Fewer redundancies
		Power Systems Domain Knowledge Management	Increased documentation on best practices for power systems subject matter expertise
	Strategic Competencies	Common Semantic Models	Adoption rate (%) of Common Semantic standards
		Interoperability	Ability to exchange data between systems
		Modularity	Ability to plug n' play HW and SW components
		Situational Awareness	Availability & accuracy of real-time grid connectivity map (%)
			Availability & accuracy of real-time telecom map (%)
		Multi-function devices/systems	Ability to demonstrate more than one function
		Fast Edge Decisions	Speed or latency of data processing of local device data (sec)
		Flexibility	Adaptibility to changes in the grid power flow
		Hybrid Distributed & Centralized Platform	Ability to augment existing legacy systems, while performing new distributed functions
	Technology Competencies	Internet Protocol (IP) Networking	Adoption rate of OSI model (%)
		Standard Interfaces	Adoption rate of Application layer interfaces (%)
		Peer-to-Peer Messaging	Adoption rate of IoT pub/sub messaging protocols (%)
		Distributed Energy Resource (DER) Integration	Relative pentration rate of seamless interconnection of DER devices & systems on the electric power grid (%)

As exhibited in Table 4-1, the balanced scorecard has provided specific measures for each objective in order to track the process of the interoperability strategy. Starting with the financial perspective, with the exception of customer retention in the customer value objective and the efficiency rating in the asset utilization objective, the majority of the measures are financial within the growth and productivity themes, such as revenue growth, average energy transaction value, and costs. In the external perspective, since the themes are centered around operational excellence and building image, only the affordability objective is the sole financial measure, while rest are non-financial indicators, such as survey ratings for satisfaction or community engagement, performance indices for reliability and safety, and amounts for number of services calls or carbon emissions. Likewise, in the internal perspective, only the reducing of capital expenditures is financial with lower supply chain costs and deferred expansion costs, while the rest, being more focused on operational processes, are measured with performance, time, or quantity metrics, such as reliability indices (e.g. SAIFI, CAIFI, SAIDI, MAIFI, CAIDI), percentage, seconds or hertz, and amount of accidents, IT integration effort, redundant assets, power losses, spinning reserves, and stability of power flow on the electric grid distribution system.

For the learning and growth perspective, all the measures are non-financial and in some cases are Boolean in the sense of whether a certain capability exists or not. In the strategic competencies theme, interoperability, modularity, multi-functional devices or systems, flexibility, and the hybrid distributed and centralized platform are each boolean metrics, while common semantic models and situational awareness are based on percentages, and fast edge decisions are measured in time units. The technology competencies theme is mainly percentage based focused with adoption rates of capabilities of IT standards like Open Interconnect Model (OSI) layers, and application layer interfaces, Internet of Things (IoT) publish-subscribe protocols, but also interested in the penetration rate of the seamless integration of DERs to the grid. Lastly, in the workforce climate theme, the metrics are mainly geared toward amounts, such as number of technical skillset certifications, truck rolls, inter-department redundancies, IT databases, and power system knowledge documentation, but also includes measures in performance and time, such as indices for condition-based maintenance and deployment time in minutes or days, respectively.

4.5 Reference Architecture

In general, a reference architecture is a proposed technical blueprint that is intended to provide suggested design guidelines to reduce the risk and accelerate the development and implementation of new technological solutions in a specific market or application. It can likewise be considered as a starting point for the end users' product or system requirements as well as a stable functional target for vendors to follow and copy. Furthermore, the comprehensive nature of a reference architecture can also advance the adoption of a new platform by expediting the realization of its respective benefits and value in an established or emerging market.

As the fourth step in the development process of this proposed research framework, this reference architecture builds off of the matrix of change (MOC) and balanced scorecard to recommend technologies for enabling interoperability in the US electric grid infrastructure. While standards and interoperability initiatives are underway in the utility sector, their collective outcomes are being narrowly applied, which have thus limited their benefits and sense of urgency in the industry (Laval et al., 2015). As the intent of this framework is to motivate and facilitate multiple stakeholders of a regulated, change-resistant, and risk-adverse industry to understand the urgency for sustainable interoperability and to change their existing operational systems' behavioral trajectory, this reference architecture was designed to holistically leverage and repackage mature off-the-shelf components, based on open standards, in a noninvasive, hassle-free, and affordable manner to unlock the benefits of modularity, situational awareness, and scalability (2015).

Since reference architectures are unprecedented in the utility industry, it is worth noting that these technological recommendations, that were assembled during the development of this framework, have already been reviewed, adopted, and copied by Duke Energy's emerging technology organization for its Distributed Intelligence Platform (DIP) reference architecture vision specification, which was created by me to document their technology roadmap and long-term strategy for mitigating their emerging challenges and anticipated evolution of the electric power system (Laval et al., 2015). Additionally, Duke Energy has explicitly attributed the need for their DIP reference architecture to the accelerated penetration of distributed energy resources (DER) systems, such as intermittent renewables, microgrids, and energy storage, that are not adequately addressed by traditional utility technologies, where its associated data is often siloed in the proprietary, prepackaged hardware, telecom, and software solutions (2015). Consequently, Duke Energy has defined their DIP reference architecture to become a vital part of an "enhanced information management system" that augments their legacy infrastructure and allows harmonious integration with future hybrid distributed and centralized systems, which require standard internet protocol (IP) communications, local interoperable data access, and distributed capabilities for security, analytics, and network management in order to deliver operational efficiencies and enhanced business intelligence (2015).

Moreover, it is important to disclose that Duke Energy's architecture vision, prior to their DIP reference architecture specification document, was centered on a distributed intelligence hardware product, referred to as a communication node, and was narrowly focused on physical connectivity requirements to the edge of grid applications with IP-based telecommunications technologies, and did not previously consider the virtual operating system environments, software middleware applications, and common semantic models that enable the virtual and logical ability to translate, exchange, and understand data between any types of asset on the power lines, substation, customer premise, central plants, and data centers (Masters, 2011). Similarly, it is important to understand that my interoperability framework's reference architecture was used as the input into Duke Energy's requirements of their hardware solution within their DIP, known now simply as just a node, in order to accommodate the ubiquitous interoperability capabilities and benefits of the virtual operating environments, software middleware, and common semantic models, that was contributed by this proposed reference architecture technical solution (Laval et al., 2015). As a result, this dissertation's reference architecture will employ the basic requirements of Duke Energy's DIP node as a hardware vehicle to not only physically retrofit to legacy equipment and support future systems, but also to host the pub/sub messaging middleware applications and necessary software data models required for translating and contextualizing operational information between devices and systems on the electric grid.

Therefore, this technical reference architecture subsection will first introduce the my newly refined concept of a node before revealing the software requirements that include internet protocol (IP) networking requirements, operating system (OS) considerations, and the field message bus (FMB) architecture that facilitate the target processes and new technology practices identified in the MOC, while also supporting the themes and objectives highlighted in the strategy map and balanced scorecard.

4.5.1 Node Platform

One of the most critical components in this reference architecture, that is responsible for housing the virtual software environment needed to enable the interoperability technology capabilities, is the node. As depicted in Figure 4-12, a node is a standards-based and modular telecommunications platform that compromises of both hardware and software components in order to offer two complimentary functions: IP connectivity and distributed computing (Laval et al., 2015).

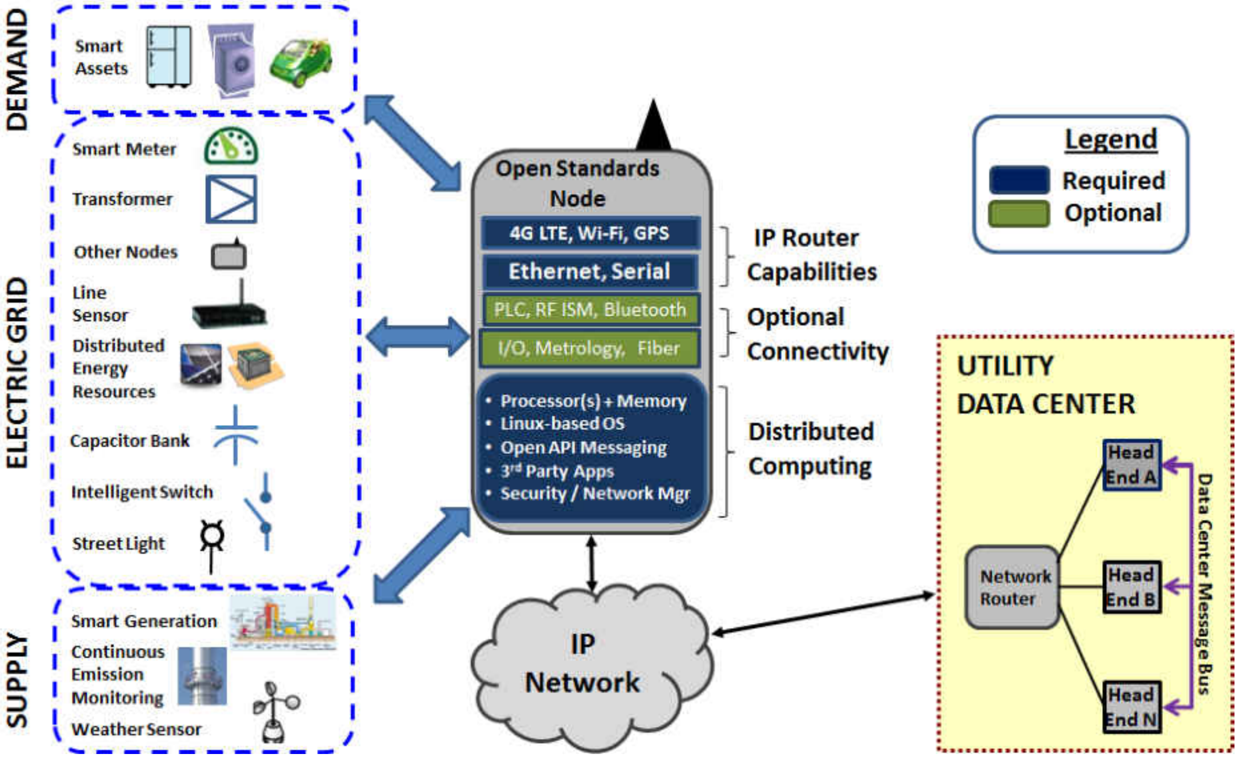


Figure 4-12: Concept of a Node Platform (Laval et al., 2015)

Without diving too much in the details of the IP router capabilities, the intent is to leverage the maturity and market commoditization of the IP-based telecommunication standard technologies, such as 4G LTE cellular, Wi-Fi, and Ethernet, for economies of scale, reliability, performance, and future-proofing, while also supporting legacy serial devices and some form of global positioning system (GPS) for geo-spatial location awareness and potentially accurate network timing characteristics. On the distributed computing side, the aim was to recommend the same basic features and functions as found in today's commercially available smart-phone that runs open applications (e.g. Android), such as processors, memory, open-source operating systems, and third party apps for open API messaging, security, and network management.

It is also important to mention that a node does not always entail installing a new piece of hardware as some of the existing smart grid devices, such as DER inverters, line sensors, phasor measurement units, smart meter concentrators or access points, intelligent gateway modems, distribution automation controllers, and home automation devices, already have the appropriate hardware fabric and thus only requires a software download to become essentially virtual node. Assuming that the node contains the proposed connectivity and computing capabilities, then the minimal functional requirements are suggested for enabling distributed intelligence (Laval et al, 2015):

- Utilize the IP network protocol
- Provide data aggregation, filtering, and prioritization of end points from multiple devices
- Support short-term storage of end-point data, audit information, and device diagnostics
- Provide routing, bridging and gateway capabilities to the IP-based networks
- Provide serial to IP conversion
- Support remote configuration and device provisioning
- Translate application level protocols between connected devices & back-office systems
- Support open standards-based, publish-subscribe messaging middleware
- Enable third-party applications via standard Application Programming Interfaces (APIs)
- Allow integration of data from legacy assets
- Provide event reporting, health monitoring, and fail-safe mechanisms

The concept of enabling distributed intelligence, via the node functional requirements above, provides the multi-functional device capabilities, fast response times, enhanced situational awareness, and scalable IT data management that can reduce the total cost of ownership, but also has the potential to improve operational efficiencies of the power system that can realize in additional cost benefits by (2015):

- Deferring capital infrastructure expansion
- Achieving improved operational performance
- Improving system response times
- More effectively managing the scalability associated with field devices
- Driving greater insight for more optimal decision making
- Streamlining the status monitoring and security of all communicating field assets
- Enabling workforce management to efficiently prioritize resources

4.5.2 Internet Protocol Networking

The IP networking capability is part of the core networking services provided for the distributed node platform and its flexible routing capability is intended to support any IP-addressable devices, while handling multiple independent IP sessions and the associated network routing, such as legacy meter-to-cash "polling" or "pass-thru" data and simultaneous publishing of operational data to a separate field message bus. In order to reap the benefits of the IP network, the OSI Model and Internet Protocol Suite, presented below in table 4-2, should be used as a reference to abstract the different layers in the stack (Antoniou, 2007; Laval et. al, 2015).

Table 4-2: OSI Model and Internet Protocol Suite with Associated Relevant Protocols

Layer	OSI Model	Internet Protocol Suite	Protocols
7	Application	Application	HTTP, SMTP, DHCP, DNS, SSH, SNMP, TLS/SSL, XML, DNP, C12, REST, MQTT, DDS, AMQP, Modbus
6	Presentation		
5	Session		
4	Transport	Transport	TCP, UDP, DCCP
3	Network	Internet	IPsec, IPv4, IPv6
2	Data Link	Network Interface	IEEE 802.3, 802.11, 802.15.4, 802.16, Bluetooth, MAC,
1	Physical		

Since a node serves as a router or gateway that can directly connect and interact with various grid assets for processing and sharing of information with other nodes and assets through standards based IP telecommunications mediums, it contains the appropriate communications technologies to decouple the network interface (OSI Model Layers 1 & 2) from the network and application interfaces (OSI Model Layers 3-7). Similarly, since a node contains ample storage, processing, and an embedded Linux environment sufficient to seamlessly enable the fast processing and secure exchange of information between disparate assets and systems on the IP network, the application Layers 5-7 are effectively decoupled from networking Layers 3-4 (Laval et al., 2015).

4.5.3 Operating System Considerations

In effort to cater toward a secure, open-source, user-friendly, and flexible application development environment, a Linux-based OS is suggested for managing the core IP networking services and drivers as well as the virtual third party node applications. It is also intended that a node device's core OS will supervise the local databases and internal processing, filtering, and aggregation of raw data from many devices into "metadata" as well as executing local analytics to perform decisions and prioritize outbound traffic in an asynchronous message queue. As displayed in Figure 4-13, the reference architecture is designed to separate the core applications in the core OS of the node from the virtual OS application environment(s) responsible for hosting the third-party software apps that include the open API field message bus, protocol adapters, distributed security, and use-case specific analytics (Laval et al., 2015).

Core OS Applications

- CPU/Memory/OS Management
- Port / Device Drivers
- Router/IP Services
- Network Management Services
- Basic Protocol Support
- SCADA pass-through
- Custom SDK API / Apps
- Device Security Services

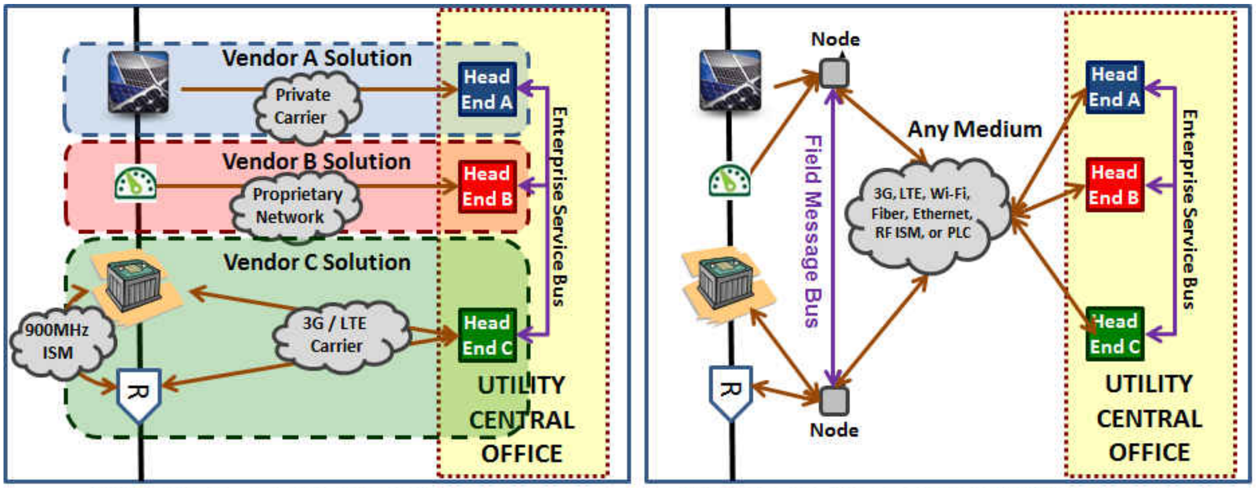
Virtual OS Applications

- Virtual Machine
- Message Bus(es)
- Open Messaging Protocols
- Protocol Adapters
- Core SDK API adapter
- Open Standard Messaging API
- 3rd Party Apps (Security/Analytics)

Figure 4-13: Example of Separate Operating System (OS) Environments (Laval et al., 2015)

4.5.4 Field Message Bus Architecture

As discovered in the research gap analysis of the literature review, the concept of the Enterprise Service Bus (ESB) in the current state of the electric grid, as illustrated in the left side of Figure 4-14, is a way to enable latent interoperability in the data center at an utility company, when modeled with a common semantic canonical structure between the integration layers of each IT head-end or operational system. However, since the field telemetry data that is polled, translated, and contextualized can be minutes, hours, or days, before being completely understood between all of the subscribing systems on the integration bus, the information being shared between field devices and systems is too late and stale to be utilized to make timely and actionable decisions for effective grid operations. Consequently, in order to optimize the value of information that is based on timeliness, location, and availability, this reference architecture has addressed the current data integration problem by defining a future platform, as depicted on the right side of Figure 4-14, that logically extends the role of ESB to the edge of the grid infrastructure in the form of a publish-subscribe (pub/sub) messaging interface, referred to as the field message bus (FMB).



Current State – Message Bus at Data Center

Future State – Message Bus in Field and Data Center

Figure 4-14: Evolution of Data Integration Paths between Grid Solutions (Laval et al., 2015)

As displayed in Figure 4-14, the FMB is an open, standards-based, pub-sub logical interface that connects multiple disparate grid devices, telecom networks, and information systems in an asynchronous, deterministic, and peer-to-peer fashion that helps facilitate interoperability between heterogeneous systems in a timely manner, which is necessary for fully realizing the value of the data for effective decision making (Laval et al., 2015). Unlike the ESB that resides in the datacenter behind head-end systems, the FMB fundamentally enables distributed control and processing across various systems or nodes in a multi-tiered hierarchy, as exhibited in Figure 4-15, which allows a seamless hybrid integration of both centralized and distributed control systems in an elegant, noninvasive, and cost-effective way (2015).

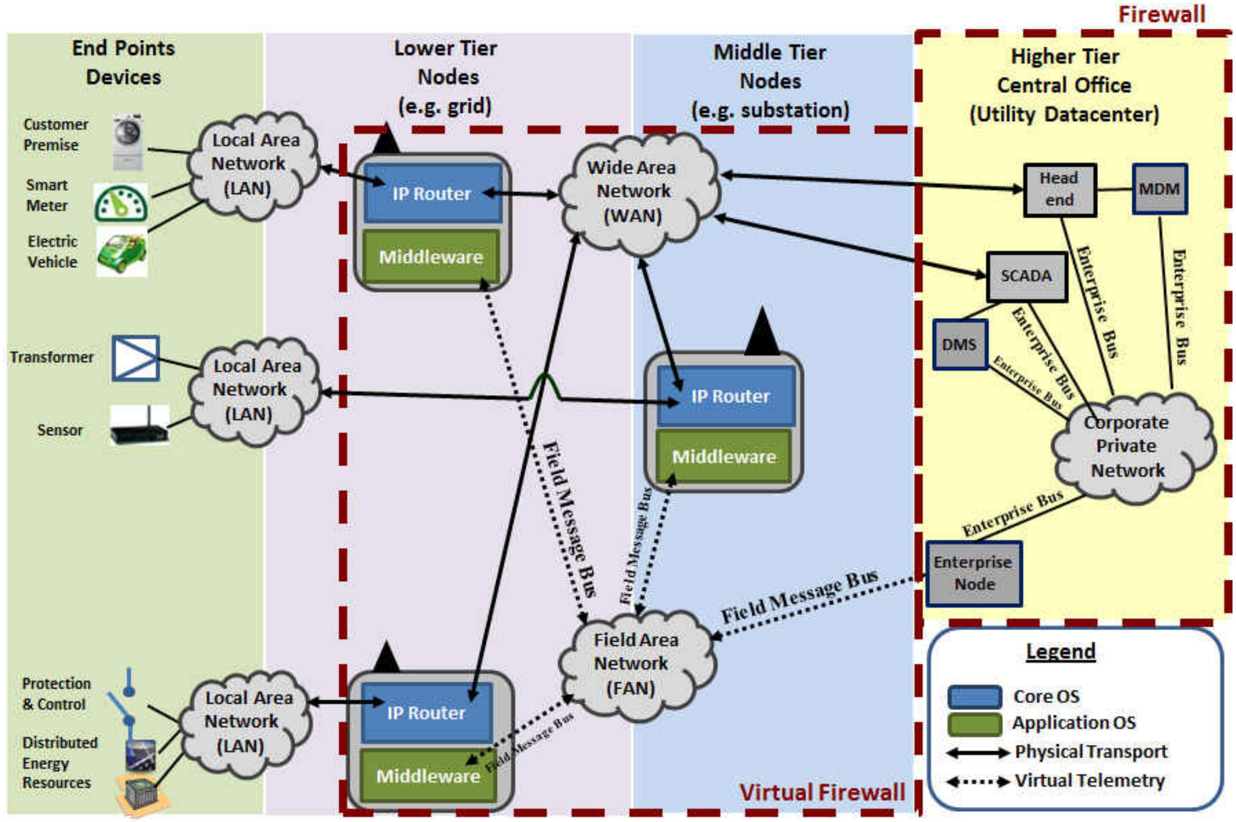


Figure 4-15: Hierarchical, Hybrid Central and Distributed FMB architecture (Laval et al., 2015)

As illustrated in Figure 4-15, the logical and hierarchical topology, of the hybrid central and distributed nodal FMB architecture, supports multiple tiers of Nodes that span across all network area domains, such as the Local Area Network (LAN), Field Area Network (FAN), and Wide Area Network (WAN). Even though from a transport perspective the data traffic is physically routed through the IP-based WAN via wired or wireless mediums, the application and logical information can be functionally shared peer-to-peer in horizontal and vertical ranking orders (Laval et al., 2015). The node hierarchy, enabled by the open pub/sub middleware that interfaces with the FMB, is important to the reliability and scalability of the system because it allows common data models and control functions to be located at the local level, which in effect off offloads certain responsibilities from the centralized control systems, such as the DMS, to delegate marching orders to lower tiered nodes (2015). This established span of control and authority can produce lower latency response times for certain delegated control functions since these individual instructions are no longer initiated from the centralized back office services. However, as the electric grid evolves and becomes populated with more intelligent devices and applications, the higher tier back-office node will still be essential for handling the centralized configuration, monitoring, and diagnostic information of the remotely deployed field devices (2015).

Another benefit of the hierarchical node reference architecture is that FMB middleware can virtually augment the existing telecom infrastructure in effort to provide enhanced capabilities without changing the pass-thru data integration path or having to bypass the polling centralized head-end systems. For example, in a conventional grid infrastructure that contains already IP routing node devices for data transport, as depicted in Figure 4-16, the traditional latencies are over 15 minutes for AMI head-ends to poll the data from all smart meters or premise telemetry devices, and over a minute for the centralized SCADA systems to poll the end points from the DER systems or protection and control equipment on the power lines or substation. This slow speed of the data integration paths is partly due to the lack of intelligence inside the devices outside the data center, but more importantly attributed to the lack of local data models and standard logical interfaces needed for interoperability between the field devices and operational systems.

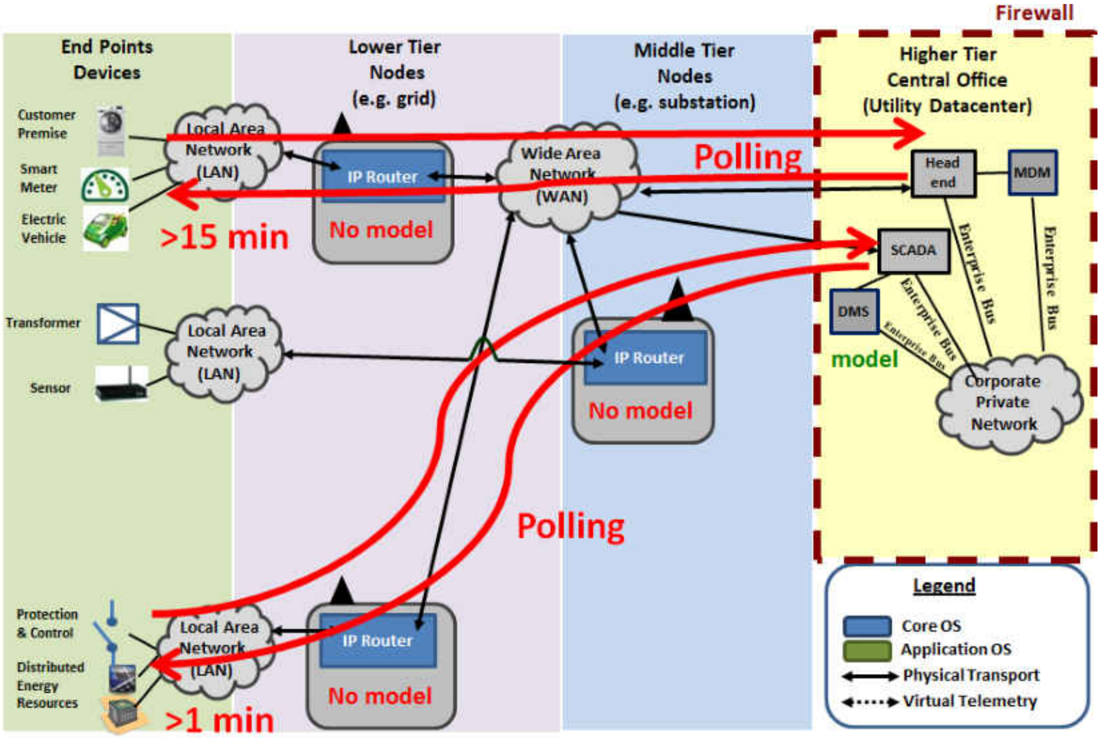


Figure 4-16: Current State of Data Integration Path without FMB Middleware or Data Model

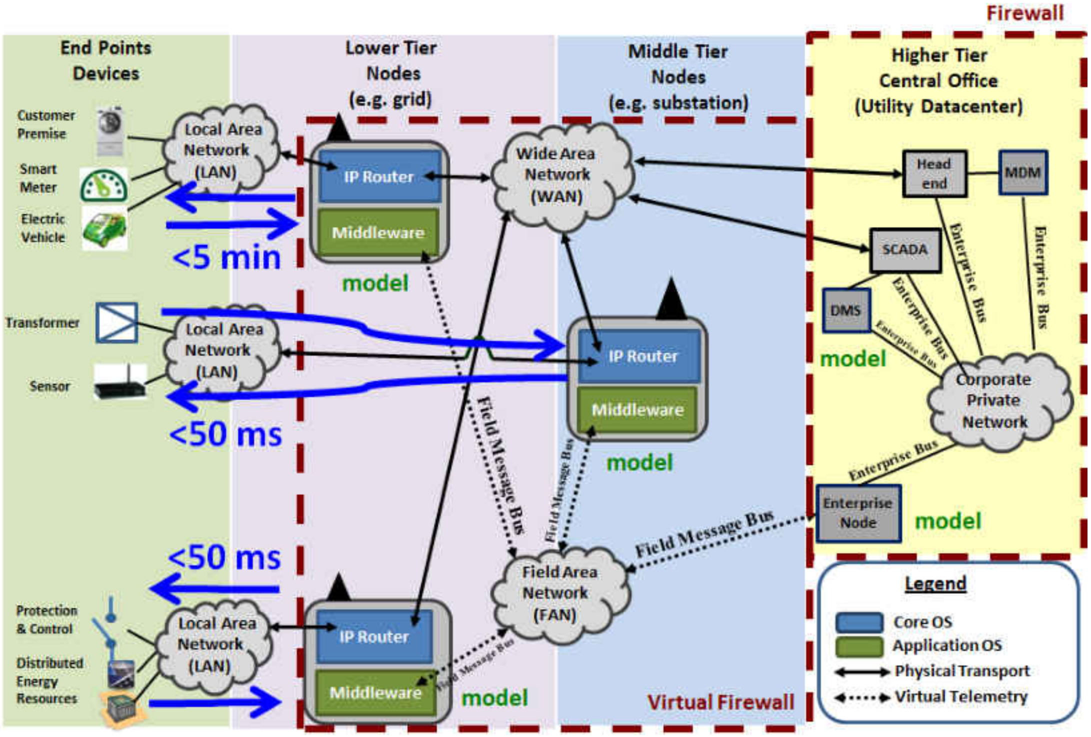


Figure 4-17: Future State of Data Integration Path with FMB Middleware and Data Model

However, by implementing this FMB reference architecture that employs pub/sub messaging middleware applications on the existing IP routing nodes, as depicted in Figure 4-17, they becomes lower tier nodes that can more quickly interrogate and poll the end point devices faster to effectively reduce the smart meters or premise device response times to less than 5 minutes and the DERs or protection and control devices down to less than 50 milliseconds or 3 cycles. As a result, this virtual capability not only provides new value from enhanced speed and security on existing nodes that continue to pass-thru data to its head-end systems, but it also offers the future flexibility to deploy data models locally on the nodes for secure, peer-to-peer interoperability in the FAN.

Figure 4-18 illustrates the conceptual data processes for this reference architecture that take place to translate and contextualize information from the field before it is stored, visualized, and analyzed for business intelligence decisions.

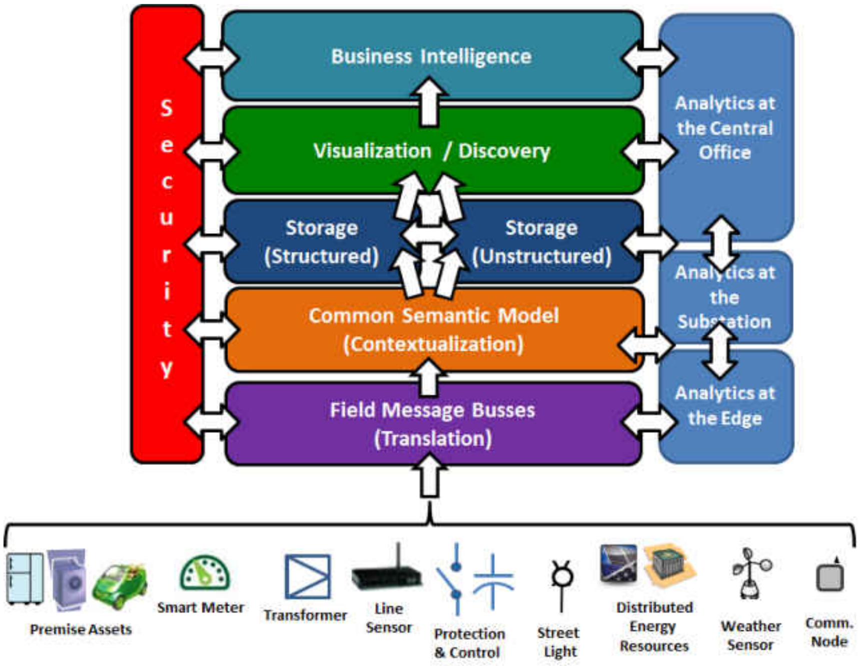


Figure 4-18: Conceptual Data Processes in the FMB Reference Architecture (Laval et al., 2015)

As shown in Figure 4-18, the reference architecture allows for the FMB pub/sub middleware to provide translation services at the edge of the network by handling the protocol translation at the device level, prior to contextualization, storage, visualization, and business intelligence steps. It also allows for integration of data and analytics across devices in the datacenter, substation, and FAN, but also supports unified security capability across all enterprise verticals. In order to elaborate on the device level protocol translation services with the FMB reference architecture, Figure 4-19 illustrates the logical elements of the FMB's virtual environment that abstracts and manages the flow of application layer data responsible for IT/OT convergence.

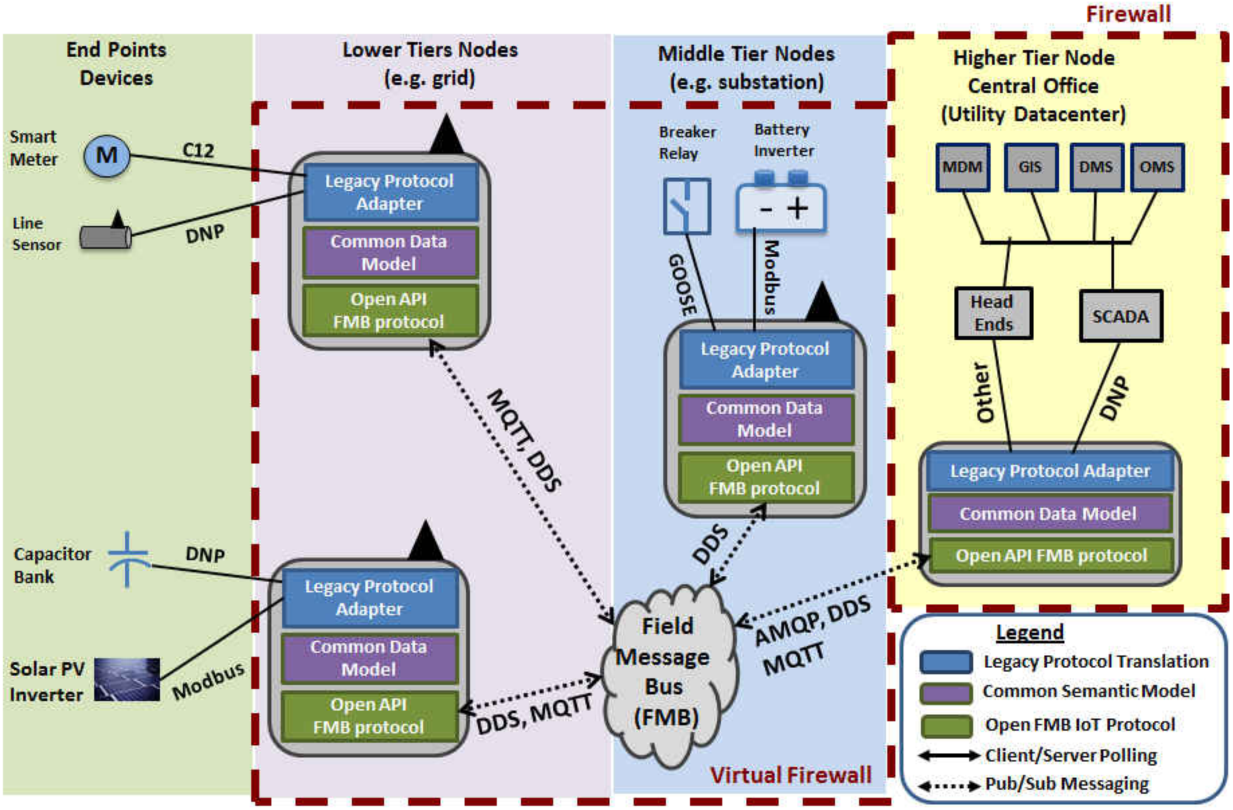


Figure 4-19: Example FMB Building Blocks for Abstracting Data Between Devices and Systems

As displayed in Figure 4-19, a middleware software application, known as an adapter, on a node translates the legacy protocol (e.g. DNP, Modbus, GOOSE) residing in an OT system or device endpoint, filters and secures its data, then converts its syntax to a standards-based IoT message bus protocol (e.g. DDS, MQTT, AMQP), where its schema conforms to a common semantic model (e.g. CIM, IEC61850). Similar to the example described in Figure 4-17, the value of the adapter is demonstrated via its constant interrogation of its connected OT systems or devices. As for the use-case application, since the data converted to the IoT pub/sub message bus protocols have an open API and conform to a common semantic model standard, the IT business logic is completely abstracted and decoupled from the OT interfaces.

Figure 4-20 exhibits the potential open API FMB building blocks that foster multiple permutations of modular and protocol-agnostic elements (Laval et. al., 2015).

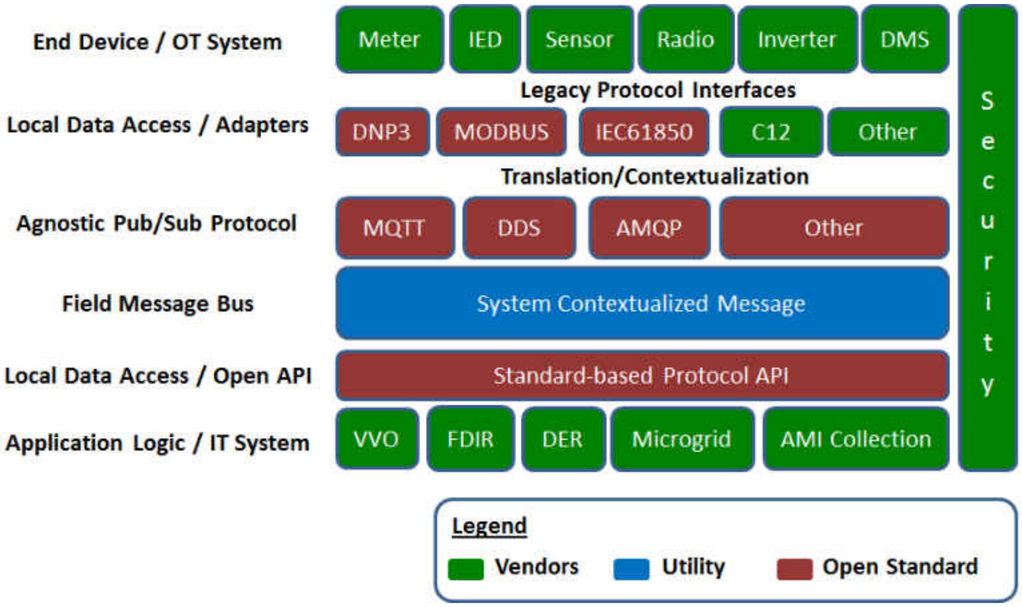


Figure 4-20: Example of External and Internal FMB Building Blocks (Laval et al., 2015)

With regard to the specified IoT pub/sub messaging protocols, in Figure 4-20, where their various advantage and disadvantages were researched and documented in the literature review section, it is recommended to employ the broker-less DDS middleware in all operational infrastructure that needs to make fast and mission-critical control decisions (e.g., DERs, microgrids, and substation automation) due its ability to enable semantic interoperability between systems in a deterministic, fault-tolerant, and extensible manner (Laval et. al, 2015). As for the other two broker-based IoT pub/sub messaging protocols, MQTT and AMQP, are recommended for consideration in lightweight telemetry devices and heavy ESB applications, respectively (2015).

Lastly, some of the capabilities and benefits that can be achieved by using this FMB architecture include (2015):

- Seamless peer-to-peer and multi-cast exchange of application layer data
- Separation of the physical, logical, and network layers of the OSI data stack
- Filtering, prioritization, compression, and translation of local real-time data
- Secure end-to-end encryption within the virtual field area network (FAN)
- Simple, lightweight, and easy to implement message bus protocols
- Agnostic to programming language, OS, and message bus protocols
- Reduced system development time via portability, reusability, and modularity
- Accommodates lower latency requirements of critical operations (e.g., DERs)
- Communication protocol integrity via quality of service, persistence, & failover
- Seamless and hassle-free migration path from central to distributed decisions
- Avoids “rip-and-replace” by translating legacy protocols to open standard API

4.6 Use-Case Application Framework

The fifth and final step in the development process is the use-case application framework, which was devised in order to assist any electric utility organization through a case study that involves data modeling, transformation, code generation, and simulation of interoperable pub/sub information exchanges between field devices to successfully execute an operational system function on the electric grid. As illustrated in Figure 4-21, the application framework consists of 3 stages before the final stage that entails clear understanding by the message-oriented middleware (MOM). These 3 stages consist of information modeling, semantic context, and message syntax.

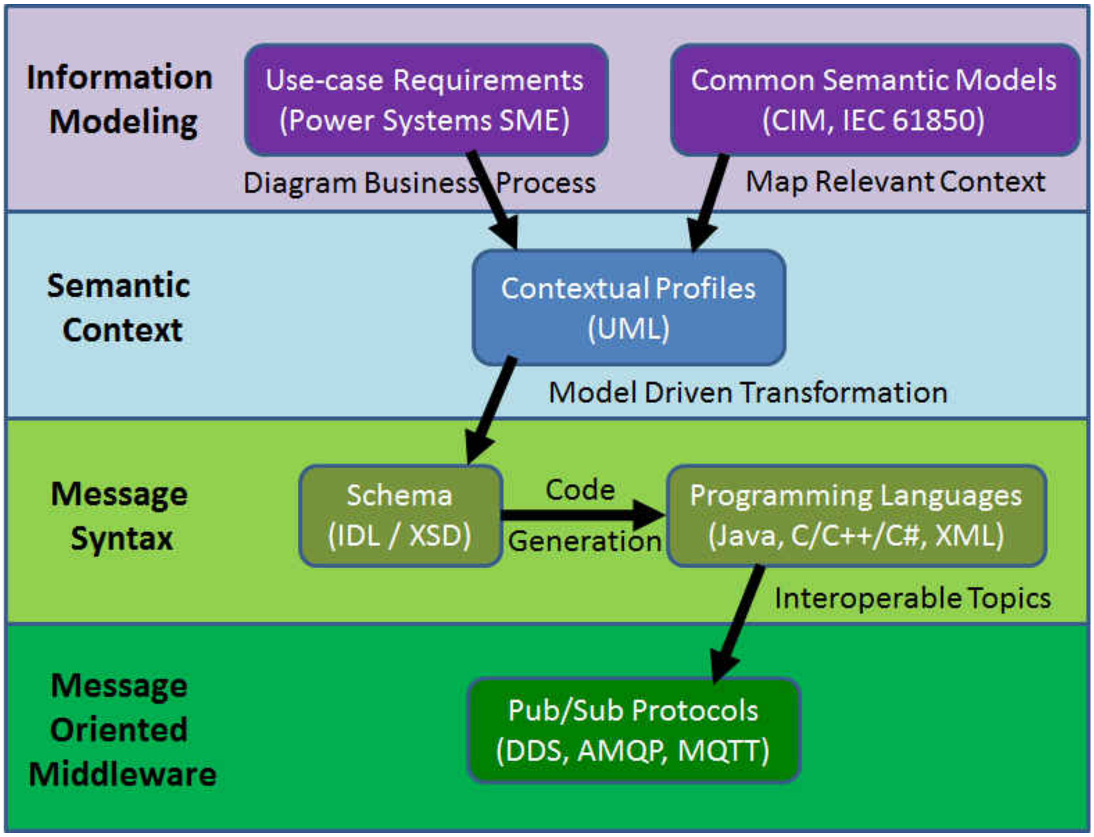


Figure 4-21: Use-case Application Framework for Interoperability on the US Electric Grid

Similar to the strategy map, the use-case application framework is a top-down process methodology, but its linkages, in contrast, flow from top to bottom. Starting with the information modeling stage, there are two complementary and parallel activities; namely, the use-case requirements and the common semantic models. Both of these activities should be modeled in a standard model-driven architecture (MDA) language, such as unified modeling language (UML), in order to ensure the power systems domain experts can effectively diagram the business process requirements and also map them to the relevant context from a common semantic model, such as IEC CIM, which is available to the public and already modeled in UML. The combination of the use-case requirements and its associated common data model is what leads to semantic context stage, which is where the UML contextual profile is created and governed. By using a commercial off-the-shelf (COTS) MDA tool, such as Sparx System's Enterprise Architect (EA), the UML representations can be traced and transformed to an industry standard schema, such in Interface description language (IDL) or extensible markup language (XML) schema definition (XSD), in the message syntax stage. Once in an IDL or XSD schema, the COTS MDA tool can automatically generate code into a binary or text format in a programming language, such as Java, C, C++, C+, or XML. To conclude the third phase, the programming language of choice that is supported by the MOM pub/sub protocol, such as DDS, MQTT, or AMQP, is then compiled and executed into topics that are published and subscribed between nodes on the FMB reference architecture that enable the peer-to-peer interoperable exchange between field devices and systems on the electric grid infrastructure.

4.7 Summary

This chapter effectively walked through various important steps of the development process for this proposed research framework that was designed to facilitate interoperability on the electric grid infrastructure at an US utility organization. The outcomes and insights from each process step were utilized and expanded upon in a cumulative fashion for each subsequent step to produce thorough organizational and technological analysis summaries for the matrix of change (MOC), strategy map, and balanced scorecard, a comprehensive technical reference architecture, and a practical case study application framework to model, simulate, and verify the interoperability interfaces in action for an operational system function on the electric grid infrastructure.

CHAPTER 5: APPLICATION OF FRAMEWORK

This chapter describes and illustrates example applications of the proposed interoperability framework at one of the largest US electric utility holding companies, Duke Energy, based in Charlotte, North Carolina. This case study, conducted by various stakeholders within Duke Energy, utilizes the reference architecture and use-case application framework, developed in Chapter 4, to facilitate an proof-of-concept project that models and implements three different use-case scenarios in effort to demonstrate and verify interoperability between various remote grid devices normally deployed in the FAN and substation as well as to operational systems.

5.1 Case Study Overview

The proposed interoperability framework, developed in Chapter 4, was utilized and applied at Duke Energy for the following 3 separate use-cases areas:

- (1) Microgrid Solar Smoothing
- (2) Inverter island detection
- (3) Fault, Location, Isolation, Sectionalization & Restoration (FLISR)

Before diving directly into the process on how each use-case was modeled in UML, mapped to a common semantic model, and implemented into a pub/sub MOM, it is important to put some context and boundaries around which components were derived from the reference architecture and how they were assembled in the use-case application framework for this case study. By using Figure 4.20 as a reference template, the relevant building blocks for this case study are depicted in Figure 5.1, where it identifies the various end devices, operational technology (OT) systems, legacy protocol adapters, open pub/sub messaging middleware, standard-based application programming interface (API), and 3 use-case applications modeled on the FMB based on the Common Information Model (CIM). Moreover, it is worth noting that the selected DDS implementation's wire protocol and API, were compliant to the Object Management Group's (OMG's) real-time publish-subscribe (RTPS) and data-centric publish-subscribe (DCPS) specifications, respectively, which guarantees interoperability between other DDS vendor implementations that comply to them.

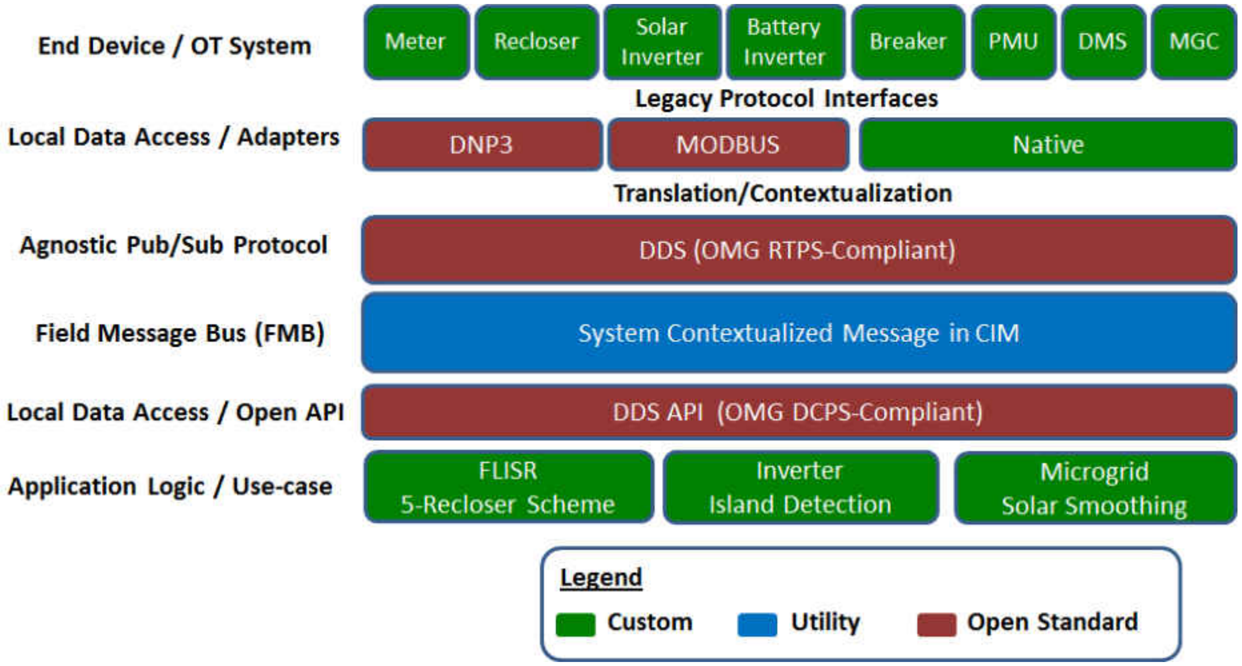


Figure 5-1: Relevant FMB Building Blocks Utilized in the Case Study using DDS and CIM

By considering and employing the relevant FMB building blocks in Figure 5-1, the data modeling and message bus protocol development process diagram in Figure 5.2 was created, based on the use-case application framework template in Figure 4.21, to represent the relevant components utilized by Duke Energy for this case study. It is also worth noting that this case study was the first documented implementation in the US electric utility industry of a UML contextual profile, that was based on the CIM standard and modeled in interface definition language (IDL), which is the appropriate schema to describe and specify the data structures in the DDS protocol. Since DDS is a binary protocol, the IDL format needs to be converted to programming language before it can be compiled by the DDS vendor implementation and the preferred language by IT engineers for this case study was java.

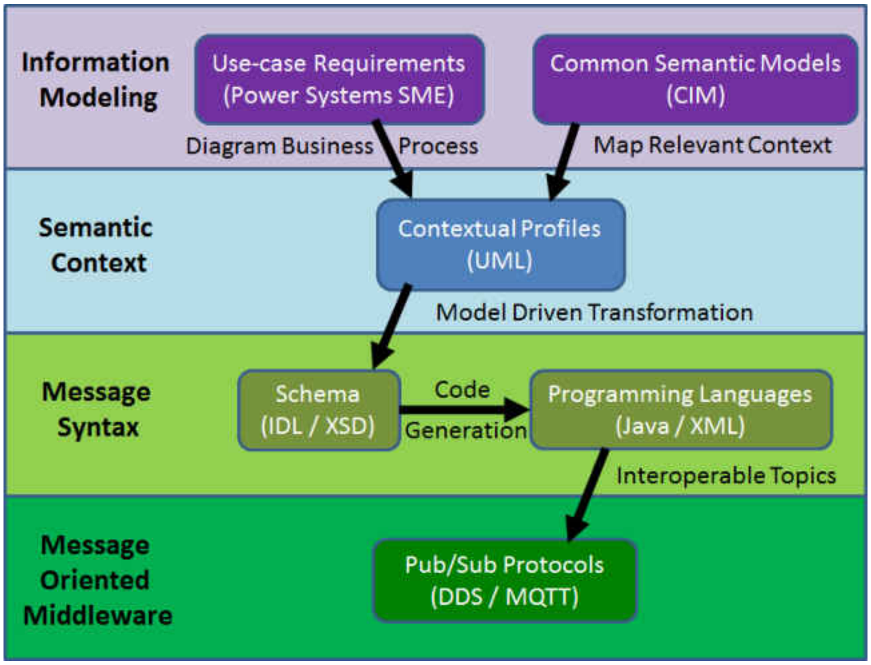


Figure 5-2: Data Modeling and Message Development Process Diagram for Case Study

Additionally, in order to help improve the transparency of the data topics on the wire MOM protocol, the FMB message syntax was also transformed to an XML Schema (XSD) that can be easily converted to a text-based format, such as XML, which is facilitated by the MQTT middleware. Once the FMB information is presented in XML, via MQTT, it can be easily ported and viewed in a standard web format, which is helpful for sharing with others, such as a panel of experts, that is ultimately needed to help facilitate the verification and validation of this interoperability framework.

Furthermore, the remaining sections in this chapter, that document the case study at Duke Energy, systematically align with the following four process diagram steps outlined in Figure 5-2: information modeling, semantic context, message syntax, and message-oriented middleware demonstration.

5.2 Information Modeling

The first step of the case study at Duke Energy that applied this interoperability framework was the information modeling phase, which consists of two important elements, namely the use-case requirements and the common semantic model reference standards. The first element, known as the use-case requirements, represents the process-oriented and behavioral aspects of the overall business models to be considered and traced in selected use-case applications and also documents the subject matter expertise of the power systems domain knowledge in a common repository that is assessable by a Model Based System Engineering (MBSE) software tool that can handle the OMG standard, Unified Modeling Language (UML). The second equally important element, known as the common semantic model reference standards, represents the object-oriented or structural aspects of the existing electric utility industry-standard data models, such as CIM, that can be ported as UML code into the MBSE tool, re-used and mapped where relevant, and extended in a consistent manner that aligns with the reference standards' data models.

5.2.1 Use-case requirements

The goal of the use-case requirements phase is to obtain, debate, and record the power systems domain knowledge in an open and collaborative manner that can be shared via an IT repository, both internally within the utility enterprise and externally to other utilities, 3rd parties, or standards organization as an option in effort to drive the adoption of the common semantic data models that are applicable to the mainstream power systems. There are many different ways, methods, and software tools that can be employed to simplify this use-case requirements' gathering-process, which ultimately develops and diagrams the interactions within the overall business models, but since this interoperability framework does not explicitly prescribe one, it was up to Duke Energy to choose their preferred method and software tool to facilitate the process. However, in order to do so, they had to first effectively recruit resources and form its use-case requirements team or internal focus group to extract the constraints of the operational functions that are being modeled on the electric grid's FAN, instead of the utility back office datacenter.

For this case study, Duke Energy was successful in developing a charter and assembling a project team that consisted of their lead enterprise IT data modeling architect, an IT architect with expertise in CIM and UML, an operations manager with extensive transmission and distribution (T&D) protection and control expertise, an IT automation engineer with back-office SCADA and DMS/EMS background, and technology development managers with expertise in DERs and microgrids, IT architecture and security, and IT application development for MOM software, such MQTT. Moreover, as recommended by the IT architects for continuity from a prior back-office enterprise CIM modeling initiative, the overall business models for each use-case in this case study were implemented with the commercial UML-based MBSE tool, Enterprise Architect (EA) by Sparx Systems.

Upon selection of the project team members and the desired MSBE tool, this Duke Energy project team devised, implemented, and documented each use-case in a consistent and cumulative fashion that principally exposed interactions and commonalities that could be leveraged where appropriate. This foundational methodology, which enables re-usability and traceability, was a top-down approach, consisting of four layers, that started with the overall use-case function at the top, followed by the requirements, then the sequence diagrams, before arriving at the bottom data model layer. This fundamental and overarching top-level business model diagramming process, that was employed throughout all use case applications in this case study, is illustrated in Figure 5.3.

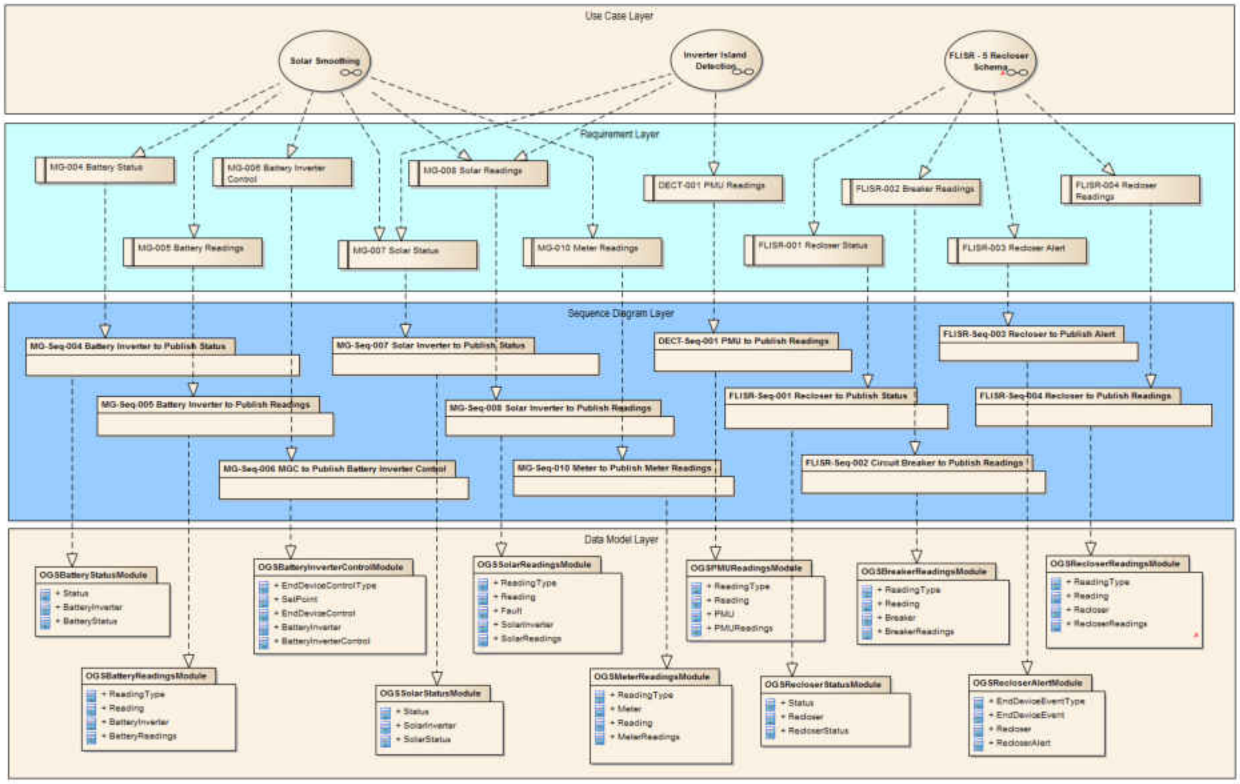


Figure 5-3: Overall Business Model Diagrams for Use-case Requirements in Case Study

However, in order to produce a consistent set of classes that define the relationships, associations, and interactions between the various layers of the overall business model diagram, as depicted in Figure 5.3, a well-organized catalog of common actors, which consists of applications and devices (that include the actual operational assets and its appropriate legacy protocol adapters), were needed to be created and stored in the master repository upfront, prior to the first layer of the diagram. As depicted in Figure 5.4, the MBSE software tool, EA, was utilized as a powerful instrument to help organize the various OT applications and the devices as a precursor to the use-case, requirements, sequence diagram and data model layers.

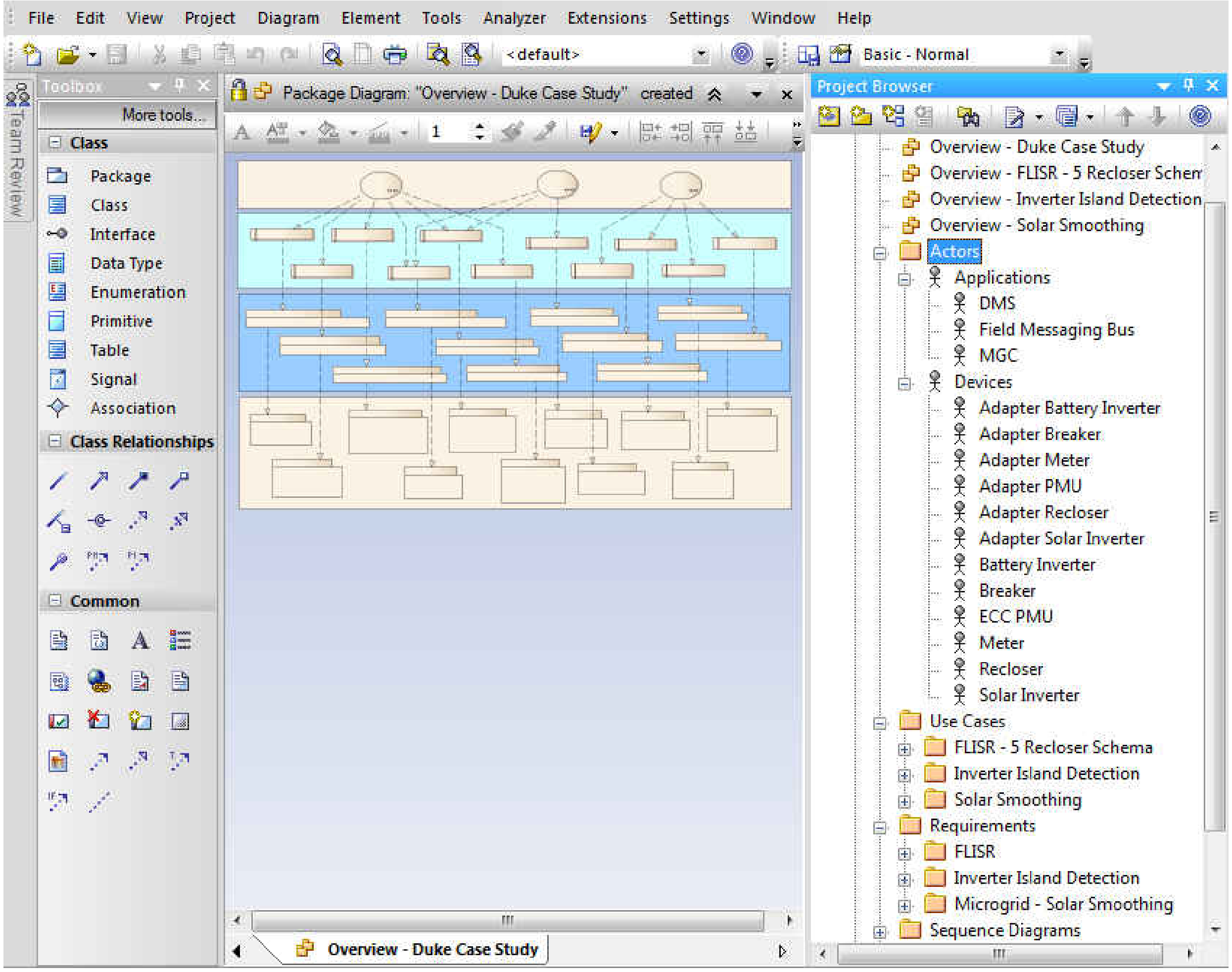


Figure 5-4: Screenshot of Case Study's Business Model, Organized in Sparx System's EA.

5.2.1.1 Use-case 1: Microgrid Solar Smoothing

This subsection describes the process and overall details for the microgrid solar smoothing application, which was the first use-case defined and implemented using this interoperability framework for the case study at Duke Energy. The business model development process for this portion of the case study contains essentially an overview description, use-case diagram, activity process diagram, list of requirements, sequence diagrams, and top-level business model for microgrid solar smoothing.

As depicted in Figure 5-5, the goal and function of the microgrid solar smoothing use-case is to utilize the application logic of a microgrid controller (MGC) to monitor the variable output of the solar PV inverter, via a power quality meter, and provide real-time control capabilities to the battery inverter on whether it needs to charge or discharge the battery in order to reduce the intermittency and fluctuations of the solar PV generation, which is impacting the combined load at the point of common coupling on the microgrid.

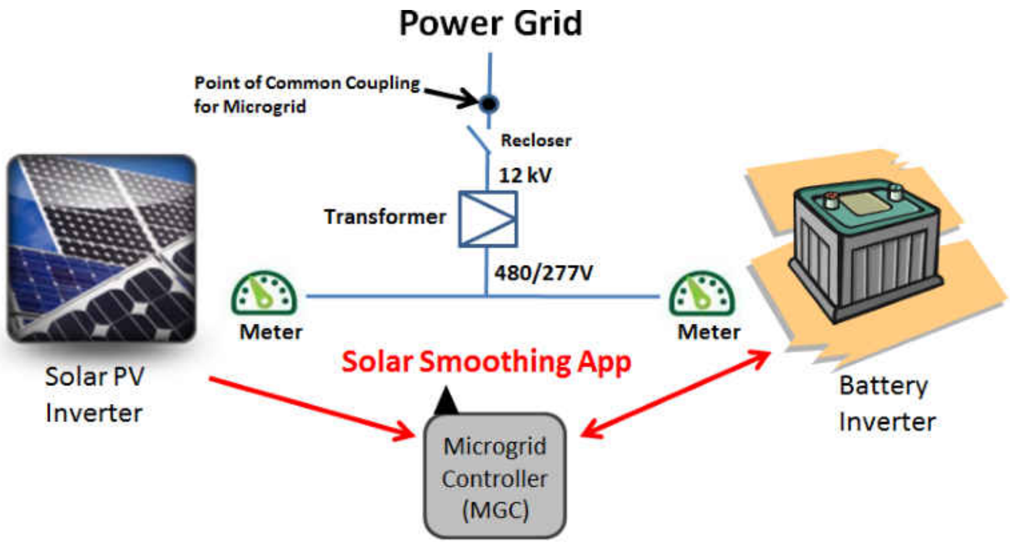


Figure 5-5: Overview of the Microgrid Solar Smoothing Use-case Description

In addition, one additional intricacy of solar smoothing functionality is that it can behavior differently, depending on whether it is in normal grid mode or in microgrid island mode. For example, in normal grid mode, the batter inverter, which operates in current-source mode, will be informed by the microgrid controller (MGC) to either increase (+) of decrease (-) load in kilowatts (kW) in order to match the solar output for smoothing. Alternatively, in microgrid island mode, the control command from the MGC will be ignored, and allows for the battery inverter to operate in voltage source mode with the universal power supply (UPS) feature, which will automatically adjusts the battery to track the load of the islanded microgrid.

Based on the overall description of the solar smoothing application provided above, the following use-case diagram was created in Figure 5-6. As illustrated below, the MGC, battery inverter, solar inverter, and meter were identified as the actors, while being linked to the 6 different types of requirements.

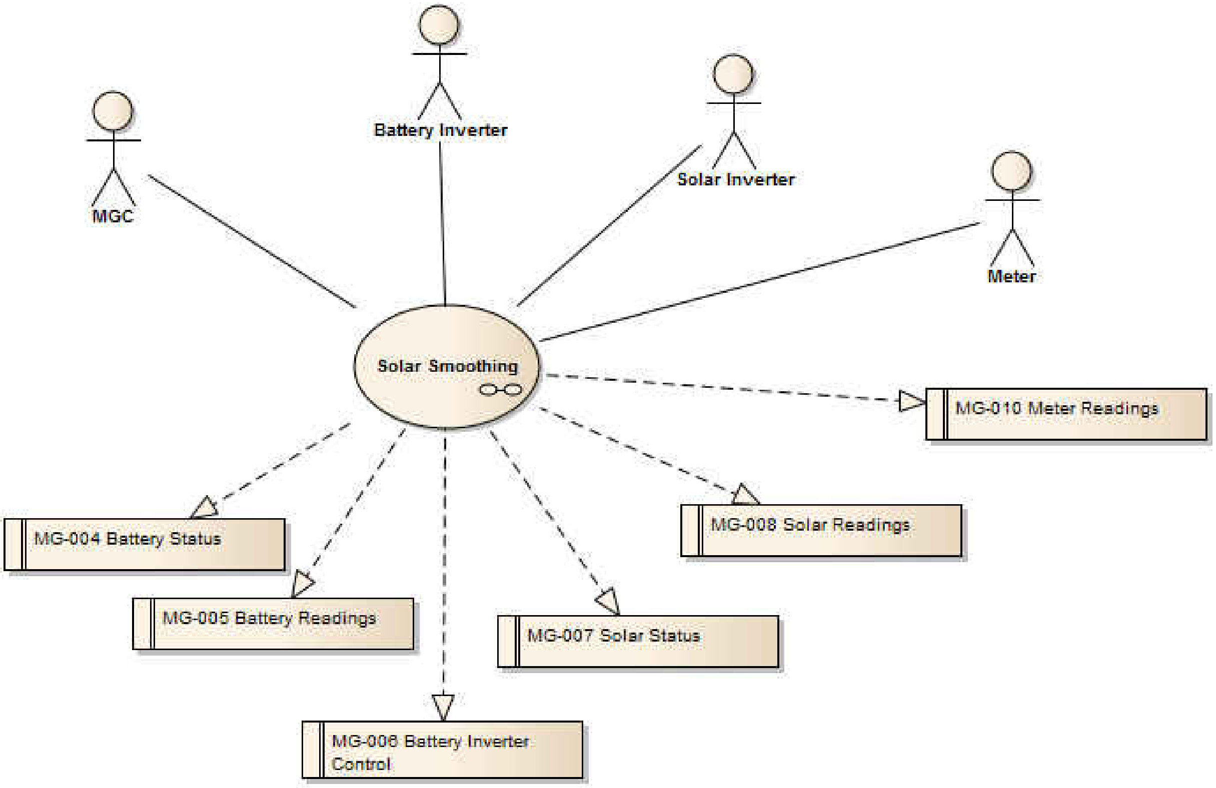
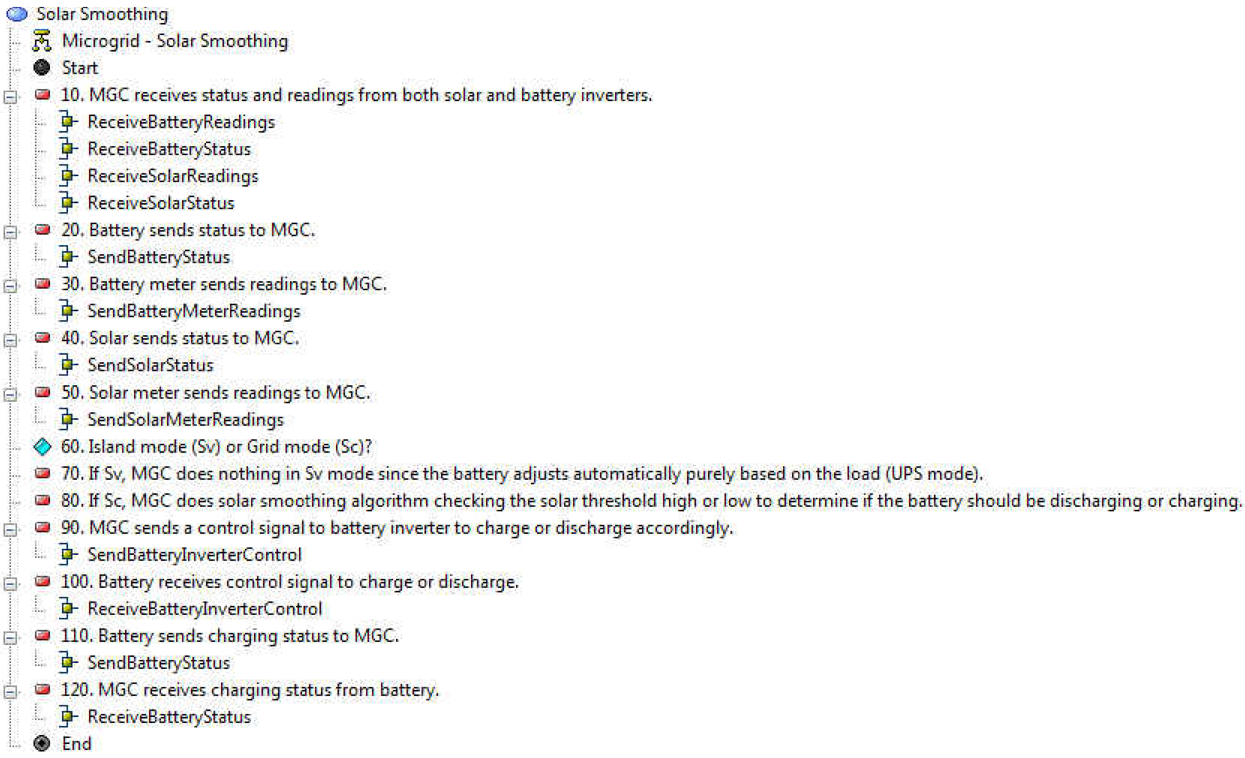


Figure 5-6: Use-case Diagram for the Microgrid Solar Smoothing Application

Another important step of the use-case layer is to map out the details of the activity process, which generates its associated activity diagram. Figure 5-7 shows the process for solar smoothing as a list of steps from the EA drop-down menu, while Figure 5-8 on the next page provides the same process steps of this use-case activity in the form of an activity diagram for the solar smoothing application. In addition, the activity diagram in Figure 5-8, provides not only the various actions or commands for each step as shown in Figure 5-7, but also provides the connectivity between actors and processes in each step. For the solar smoothing application, the first 5 steps, namely 10, 20, 30, 40, and 50, are data publishing steps of readings or status, while step 60, is the fork that determines what type of control the battery inverter needs to do.



- Solar Smoothing
  - Microgrid - Solar Smoothing
  - Start
  - 10. MGC receives status and readings from both solar and battery inverters.
    - ReceiveBatteryReadings
    - ReceiveBatteryStatus
    - ReceiveSolarReadings
    - ReceiveSolarStatus
  - 20. Battery sends status to MGC.
    - SendBatteryStatus
  - 30. Battery meter sends readings to MGC.
    - SendBatteryMeterReadings
  - 40. Solar sends status to MGC.
    - SendSolarStatus
  - 50. Solar meter sends readings to MGC.
    - SendSolarMeterReadings
  - 60. Island mode (Sv) or Grid mode (Sc)?
  - 70. If Sv, MGC does nothing in Sv mode since the battery adjusts automatically purely based on the load (UPS mode).
  - 80. If Sc, MGC does solar smoothing algorithm checking the solar threshold high or low to determine if the battery should be discharging or charging.
  - 90. MGC sends a control signal to battery inverter to charge or discharge accordingly.
    - SendBatteryInverterControl
  - 100. Battery receives control signal to charge or discharge.
    - ReceiveBatteryInverterControl
  - 110. Battery sends charging status to MGC.
    - SendBatteryStatus
  - 120. MGC receives charging status from battery.
    - ReceiveBatteryStatus
  - End

Figure 5-7: Activity Process list for the Microgrid Solar Smoothing Use-case

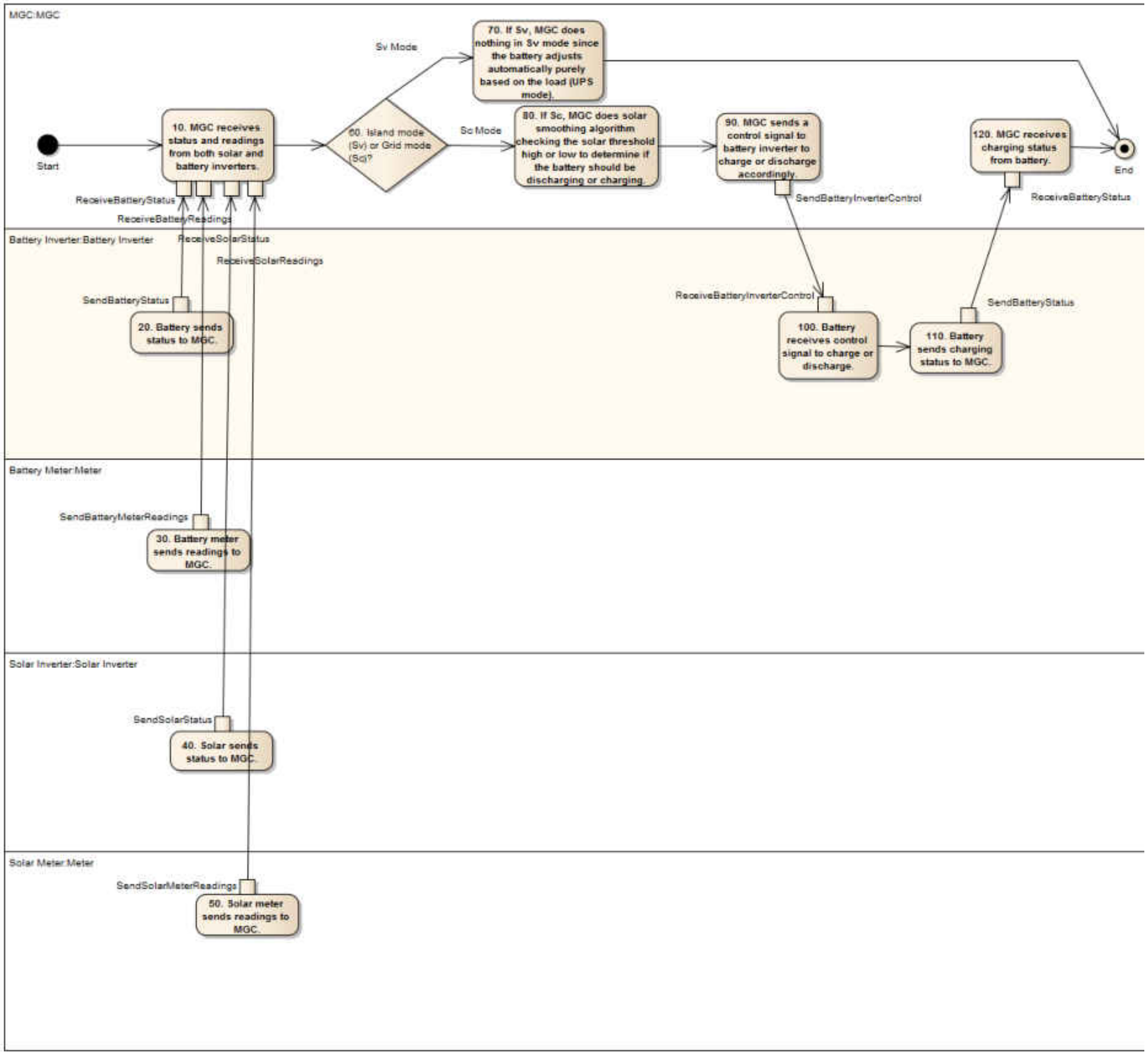
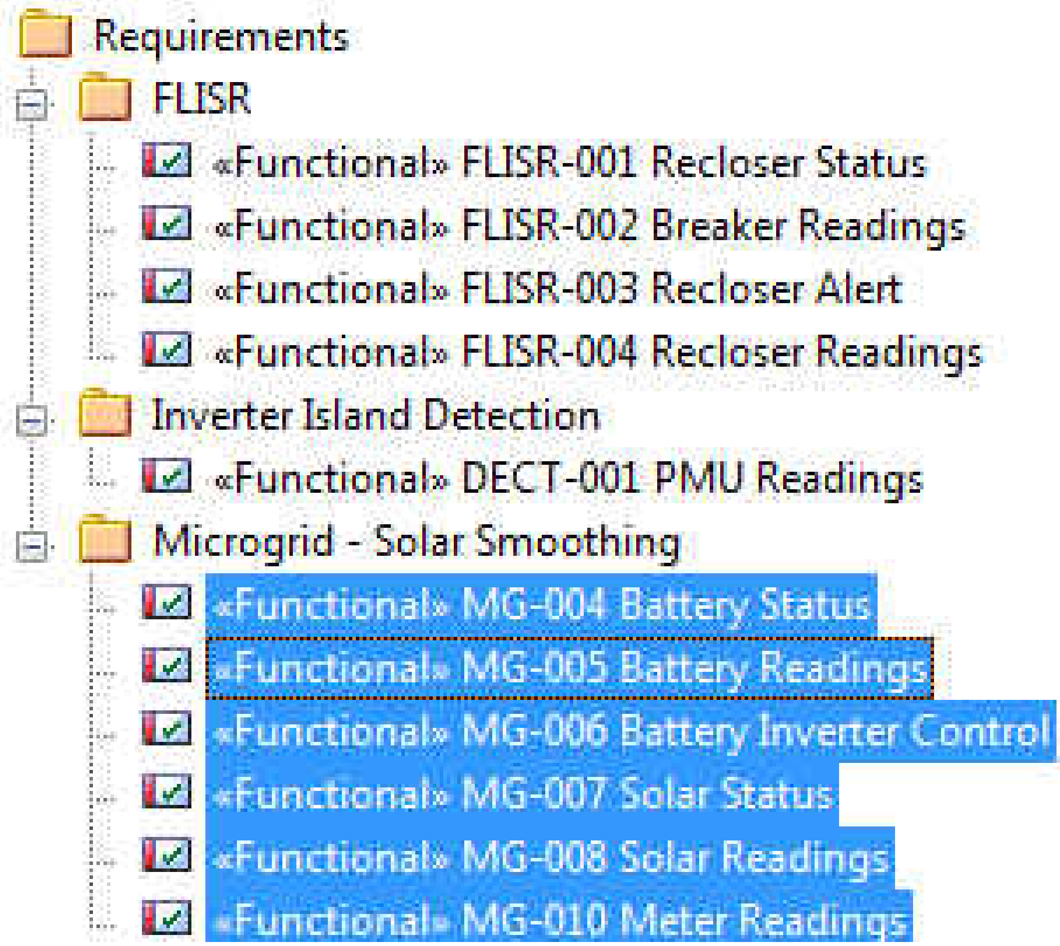


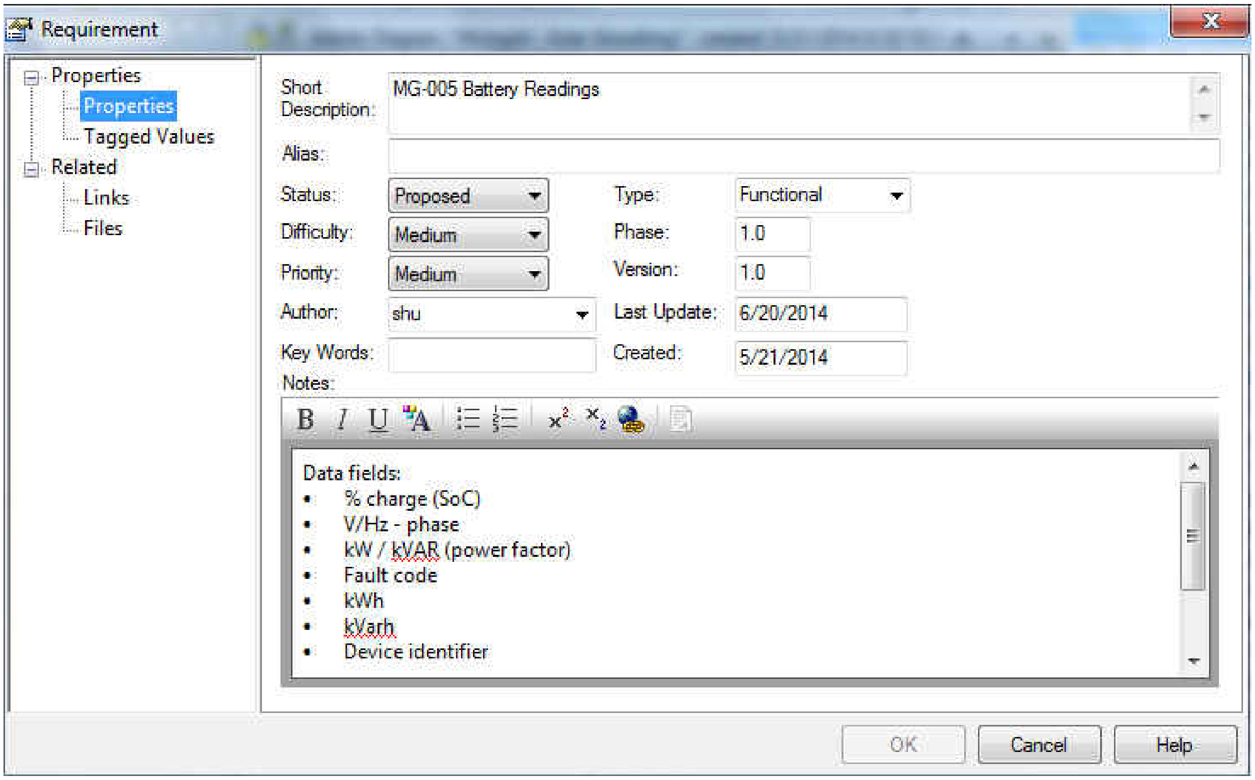
Figure 5-8: Activity Diagram for the Microgrid Solar Smoothing Use-case

After the activity diagram was generated, the list of requirements was defined for the 6 functions highlighted and displayed below in Figure 5-9. Using EA, each separate requirement had to be entered to describe the mandatory data fields for each function. For microgrid solar smoothing, an example screenshot from the properties tab of the battery readings requirement, showed in Figure 5-10, reveals the various data fields required for this use-case function, such as state of charge, phase, power factor, fault code, real power capacity, reactive power capacity, and the device identifier.



- Requirements
  - FLISR
    - «Functional» FLISR-001 Recloser Status
    - «Functional» FLISR-002 Breaker Readings
    - «Functional» FLISR-003 Recloser Alert
    - «Functional» FLISR-004 Recloser Readings
  - Inverter Island Detection
    - «Functional» DECT-001 PMU Readings
  - Microgrid - Solar Smoothing
    - «Functional» MG-004 Battery Status
    - «Functional» MG-005 Battery Readings
    - «Functional» MG-006 Battery Inverter Control
    - «Functional» MG-007 Solar Status
    - «Functional» MG-008 Solar Readings
    - «Functional» MG-010 Meter Readings

Figure 5-9: List of Requirements for Microgrid Solar Smoothing



Short Description: MG-005 Battery Readings

Alias:

Status: Proposed

Type: Functional

Difficulty: Medium

Phase: 1.0

Priority: Medium

Version: 1.0

Author: shu

Last Update: 6/20/2014

Key Words:

Created: 5/21/2014

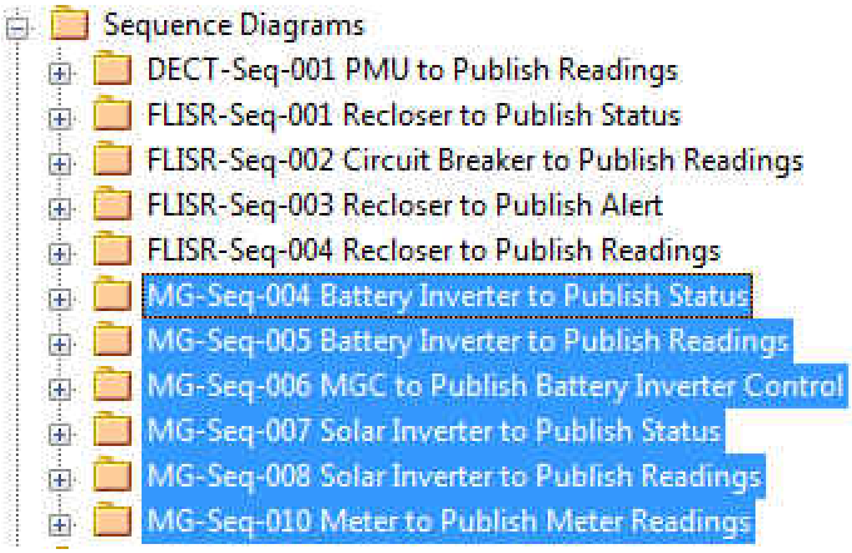
Notes:

Data fields:

- % charge (SoC)
- V/Hz - phase
- kW / kVAR (power factor)
- Fault code
- kWh
- kVarh
- Device identifier

Figure 5-10: Example Requirement Tab for the Battery Readings Function

After inputting and completing the various requirements of the 6 functions into EA, the sequence diagrams were next generated for this use-case in Figure 5-11. For microgrid solar smoothing, an example sequence diagram is represented for the battery inverter to publish reading function in Figure 5-12. In this sequence diagram, the various legacy protocol of the battery inverter, such as Modbus, and its converting adapter to CIM are evident in the publishing action, while the subscribing action of the microgrid controller (MGC) to the FMB infers that the MGC has already been adapted from its native format to CIM.



Sequence Diagrams
DECT-Seq-001 PMU to Publish Readings
FLISR-Seq-001 Recloser to Publish Status
FLISR-Seq-002 Circuit Breaker to Publish Readings
FLISR-Seq-003 Recloser to Publish Alert
FLISR-Seq-004 Recloser to Publish Readings
MG-Seq-004 Battery Inverter to Publish Status
MG-Seq-005 Battery Inverter to Publish Readings
MG-Seq-006 MGC to Publish Battery Inverter Control
MG-Seq-007 Solar Inverter to Publish Status
MG-Seq-008 Solar Inverter to Publish Readings
MG-Seq-010 Meter to Publish Meter Readings

Figure 5-11: List of Sequence Diagrams for the Microgrid Solar Smoothing Use-case

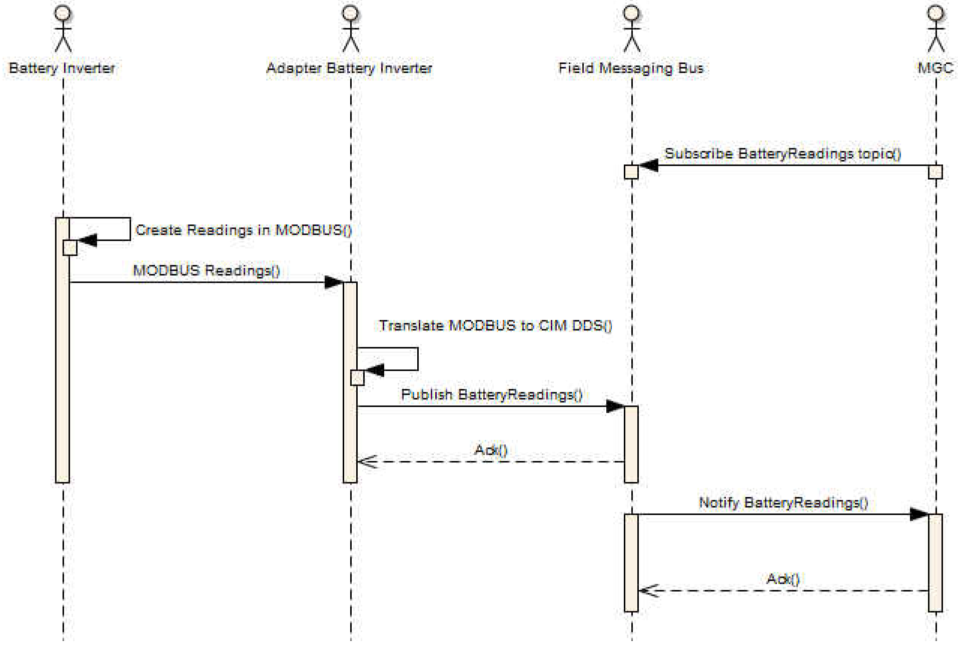


Figure 5-12: Example Sequence Diagram for Battery Inverter to Publish Reading Action

Lastly, upon completion of the first three layers, the top-level business model for microgrid solar smoothing use-case was produced in Figure 5-13, which also connects them to the data model layer, which is covered in more detail later in section 5.2.2.

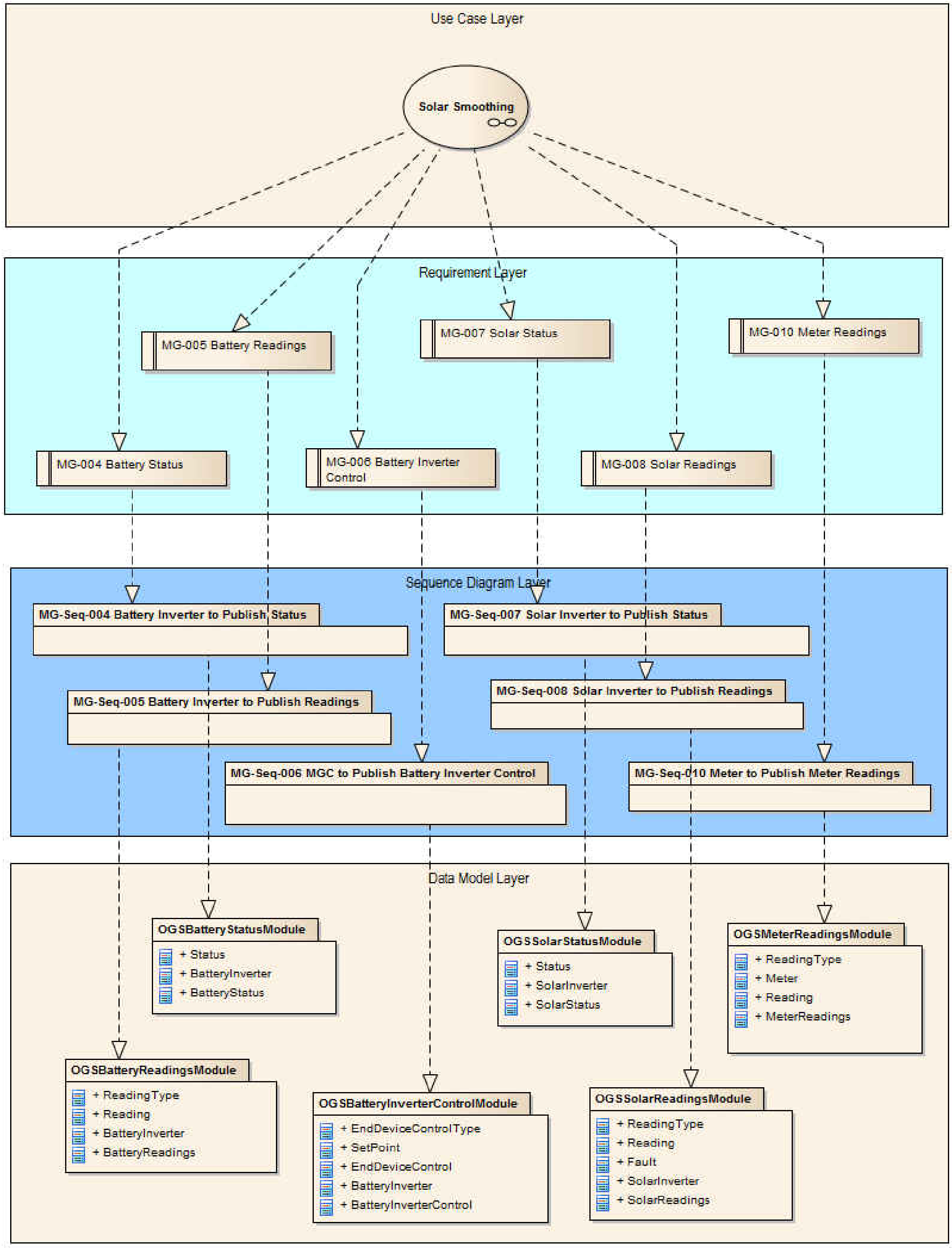


Figure 5-13: Top-level Business Model for the Microgrid Solar Smoothing Use-case

5.2.1.2 Use-case 2: Inverter Island Detection

This subsection describes the process and overall details for the inverter island detection application, which was the second use-case devised and developed using this interoperability framework for the case study at Duke Energy. Similar to the microgrid solar smoothing, the development process for this application contains an overview description, use-case diagram, activity process diagram, list of requirements, sequence diagrams, and top-level business model for inverter island detection.

As depicted in Figure 5-14, the purpose and objective of the inverter island detection use-case is to ensure the DG asset, such as a solar PV inverter, has WAN access, via telecommunications, to the high resolution and time-sensitive load data for each phase, via phasor measurement units (PMUs), at a reference point on the power system, such as the substation or energy control center (ECC). The smart inverters have built-in functions to respond appropriately when receiving PMU readings.

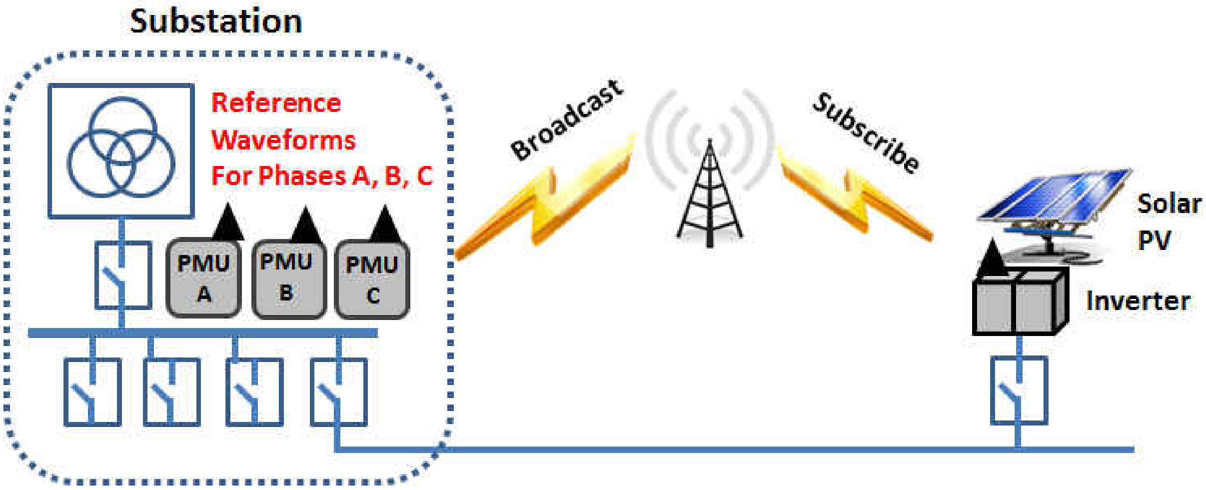


Figure 5-14: Overview of the Inverter Island Detection Use-case Description

Based on the overall description of the inverter island detection application provided above, the following use-case diagram was created in Figure 5-15. As illustrated below, the solar inverter and ECC PMU were identified as the actors, while being linked to the 3 different types of requirements.

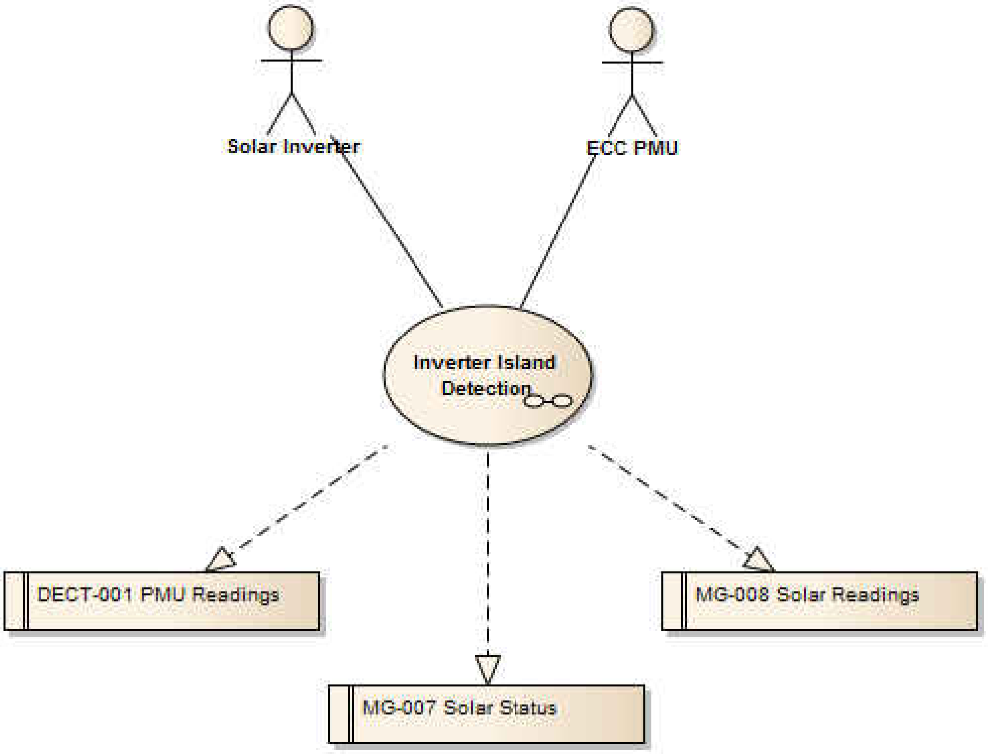
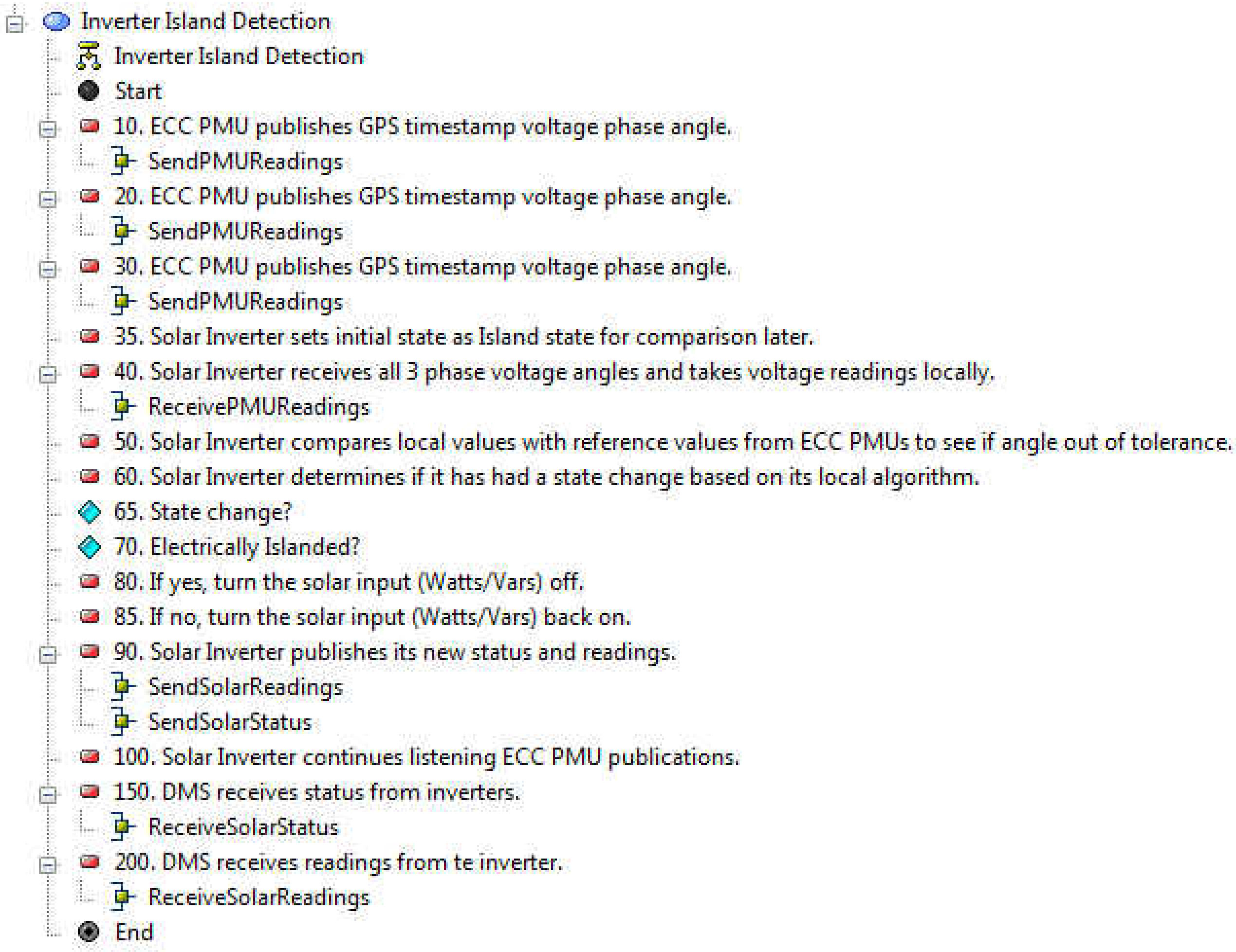


Figure 5-15: Use-case diagram for the Inverter Island Detection Application

Figure 5-16 on the next page shows the process for inverter island detection as a list of steps that includes the actions and commands, while Figure 5-17 on the following page provides the same process steps of this use-case activity in the form of an activity diagram. For the inverter island detection application, the first 3 steps, namely 10, 20, and 30, are data publishing steps of readings from the ECC PMU's with a GPS timestamp, while step 35 is where the solar inverter has some internal initial states to compare against the PMU readings received in step 40. Step 50 is when the inverter comparison against the reference occurs. While steps 60, 65, and 70 are where the determination of a state change is decided and processed. Steps 80 and 85 are the decision trees, and Steps 90, 100, 150, 200 are where the status and solar readings are published.



- Inverter Island Detection
  - Inverter Island Detection
  - Start
  - 10. ECC PMU publishes GPS timestamp voltage phase angle.
    - SendPMUReadings
  - 20. ECC PMU publishes GPS timestamp voltage phase angle.
    - SendPMUReadings
  - 30. ECC PMU publishes GPS timestamp voltage phase angle.
    - SendPMUReadings
  - 35. Solar Inverter sets initial state as Island state for comparison later.
  - 40. Solar Inverter receives all 3 phase voltage angles and takes voltage readings locally.
    - ReceivePMUReadings
  - 50. Solar Inverter compares local values with reference values from ECC PMUs to see if angle out of tolerance.
  - 60. Solar Inverter determines if it has had a state change based on its local algorithm.
  - 65. State change?
  - 70. Electrically Islanded?
  - 80. If yes, turn the solar input (Watts/Vars) off.
  - 85. If no, turn the solar input (Watts/Vars) back on.
  - 90. Solar Inverter publishes its new status and readings.
    - SendSolarReadings
    - SendSolarStatus
  - 100. Solar Inverter continues listening ECC PMU publications.
  - 150. DMS receives status from inverters.
    - ReceiveSolarStatus
  - 200. DMS receives readings from te inverter.
    - ReceiveSolarReadings
  - End

Figure 5-16: Activity Process List for the Inverter Island Detection Use-case

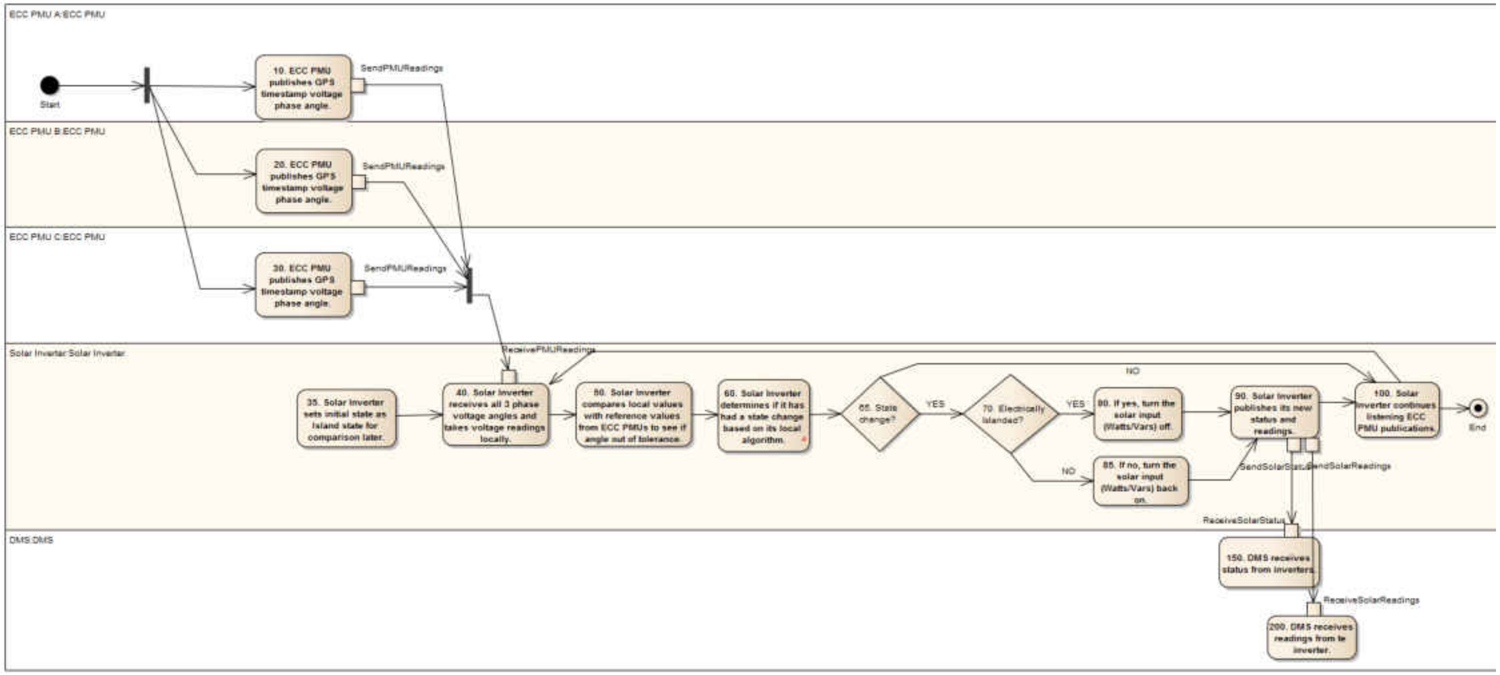
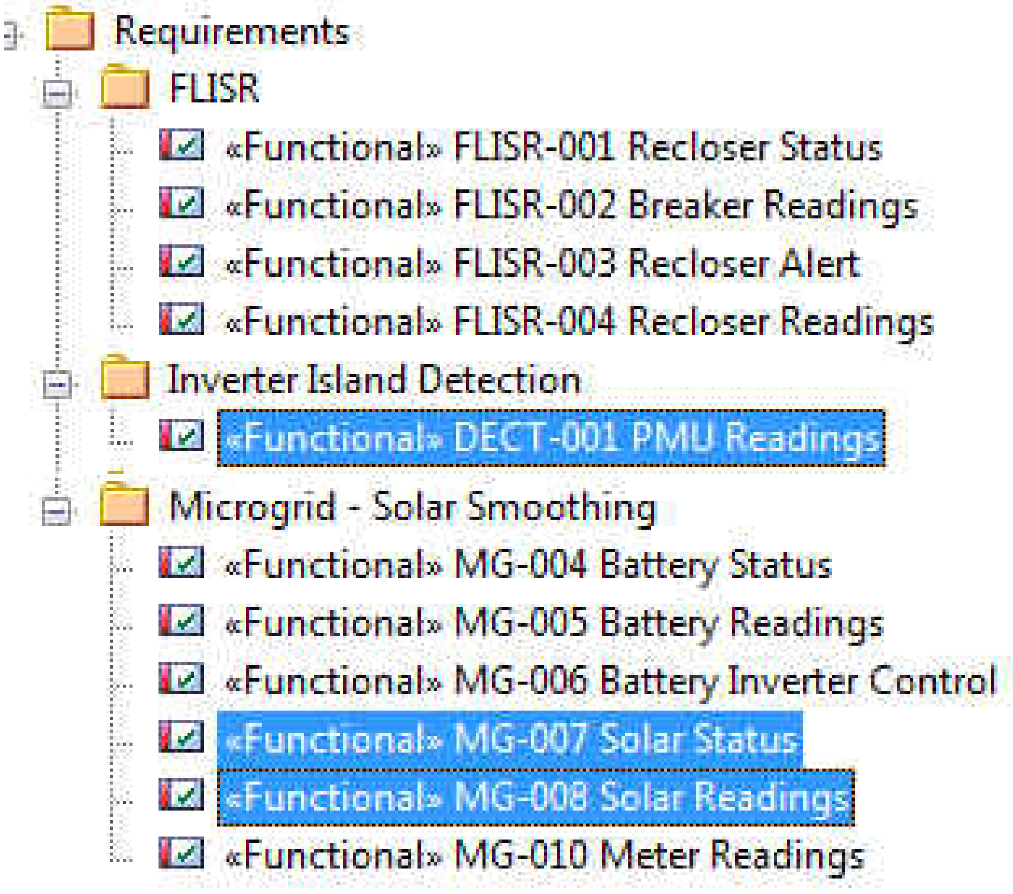


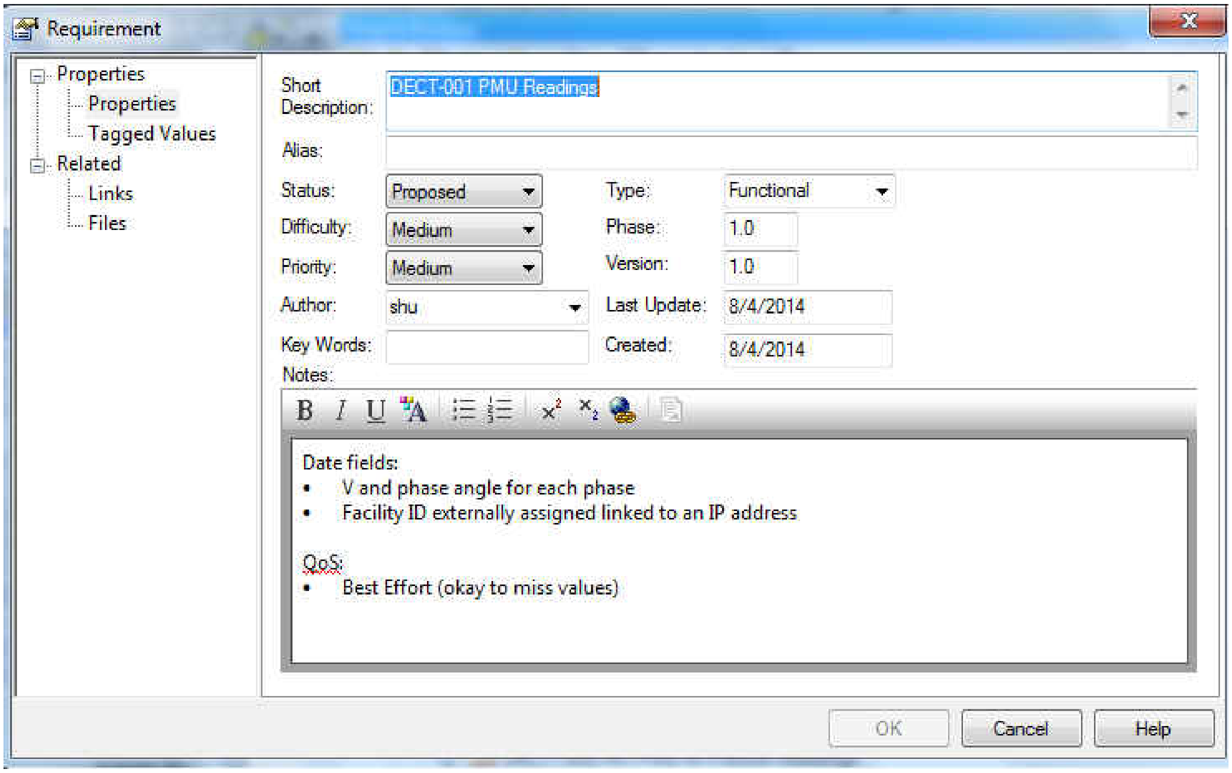
Figure 5-17: Activity Diagram for the Inverter Island Detection Use-case

After the activity diagram was generated, the list of requirements was defined for the 3 functions highlighted and displayed below in Figure 5-18. Using EA and leveraging the 2 previously defined functions in microgrid solar smoothing, only one separate requirement had to be entered to describe the mandatory data fields for this second use-case. For inverter island detection, an example screenshot from the properties tab of the PMU readings requirement, showed in Figure 5-19, reveals the various data fields required for this use-case function, such as voltage, phase angle, power factor, and facility ID.



- Requirements
  - FLISR
    - «Functional» FLISR-001 Recloser Status
    - «Functional» FLISR-002 Breaker Readings
    - «Functional» FLISR-003 Recloser Alert
    - «Functional» FLISR-004 Recloser Readings
  - Inverter Island Detection
    - «Functional» DECT-001 PMU Readings
  - Microgrid - Solar Smoothing
    - «Functional» MG-004 Battery Status
    - «Functional» MG-005 Battery Readings
    - «Functional» MG-006 Battery Inverter Control
    - «Functional» MG-007 Solar Status
    - «Functional» MG-008 Solar Readings
    - «Functional» MG-010 Meter Readings

Figure 5-18: List of Requirements for Inverter Island Detection



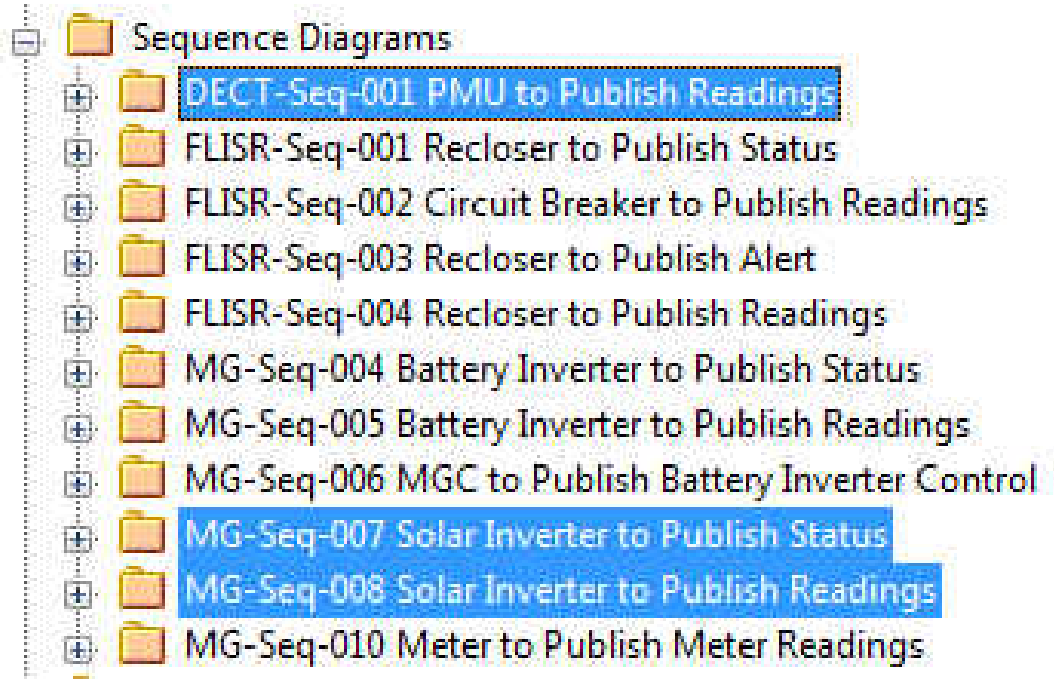
Short Description: DECT-001 PMU Readings
Alias:
Status: Proposed
Type: Functional
Difficulty: Medium
Phase: 1.0
Priority: Medium
Version: 1.0
Author: shu
Last Update: 8/4/2014
Key Words:
Created: 8/4/2014
Notes:

Date fields:
- V and phase angle for each phase
- Facility ID externally assigned linked to an IP address

QoS:
- Best Effort (okay to miss values)

Figure 5-19: Example Requirement Tab for the PMU Readings Function

After inputting the 1 new PMU function, the associated PMU sequence diagram along with the 2 re-used sequence diagrams from microgrid solar smoothing were highlighted in Figure 5-20 and included in the list of sequence diagrams for this use-case. For inverter island detection, the new sequence diagram is represented for the PMU to publish reading function in Figure 5-21. In this sequence diagram, the native format of the PMU is converted to CIM DDS before being published to the FMB that is being subscribed to by the solar PV inverter adapter that translates it back to a legacy protocol, Modbus.



Sequence Diagrams

- DECT-Seq-001 PMU to Publish Readings
- FLISR-Seq-001 Recloser to Publish Status
- FLISR-Seq-002 Circuit Breaker to Publish Readings
- FLISR-Seq-003 Recloser to Publish Alert
- FLISR-Seq-004 Recloser to Publish Readings
- MG-Seq-004 Battery Inverter to Publish Status
- MG-Seq-005 Battery Inverter to Publish Readings
- MG-Seq-006 MGC to Publish Battery Inverter Control
- MG-Seq-007 Solar Inverter to Publish Status
- MG-Seq-008 Solar Inverter to Publish Readings
- MG-Seq-010 Meter to Publish Meter Readings

Figure 5-20: List of Sequence Diagrams for the Inverter Island Detection Use-case

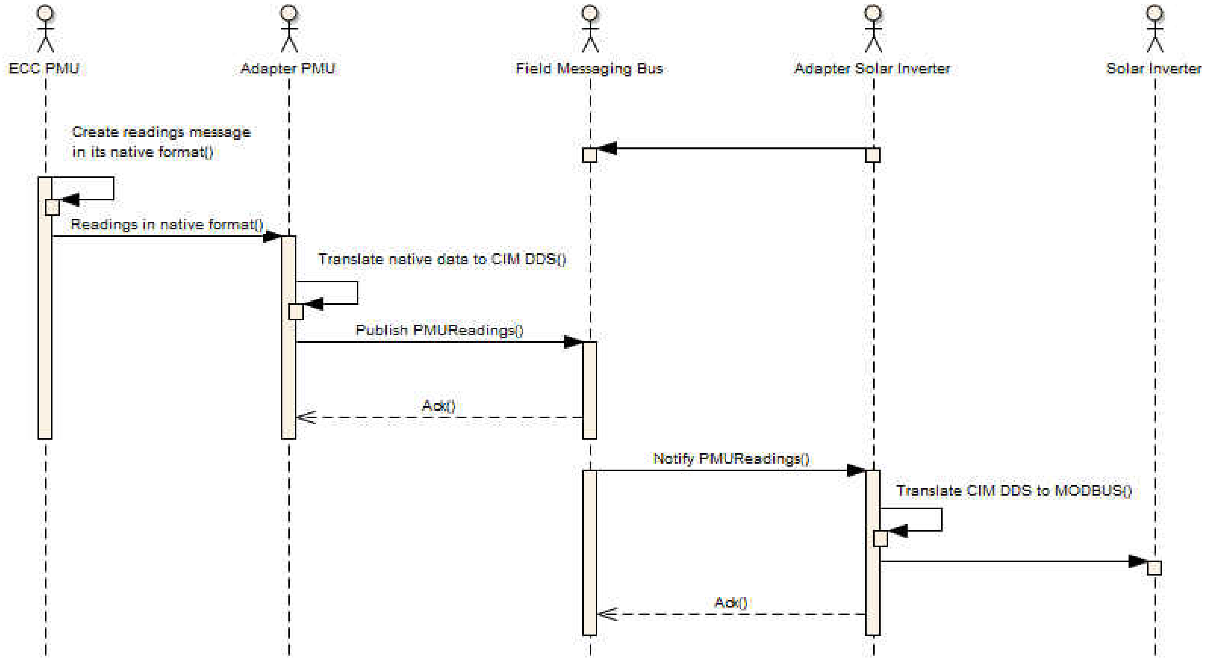


Figure 5-21: Example Sequence Diagram for PMU to Publish Reading Action

Similar to the previous use-case, the top-level business model for inverter island detection was produced in Figure 5-22.

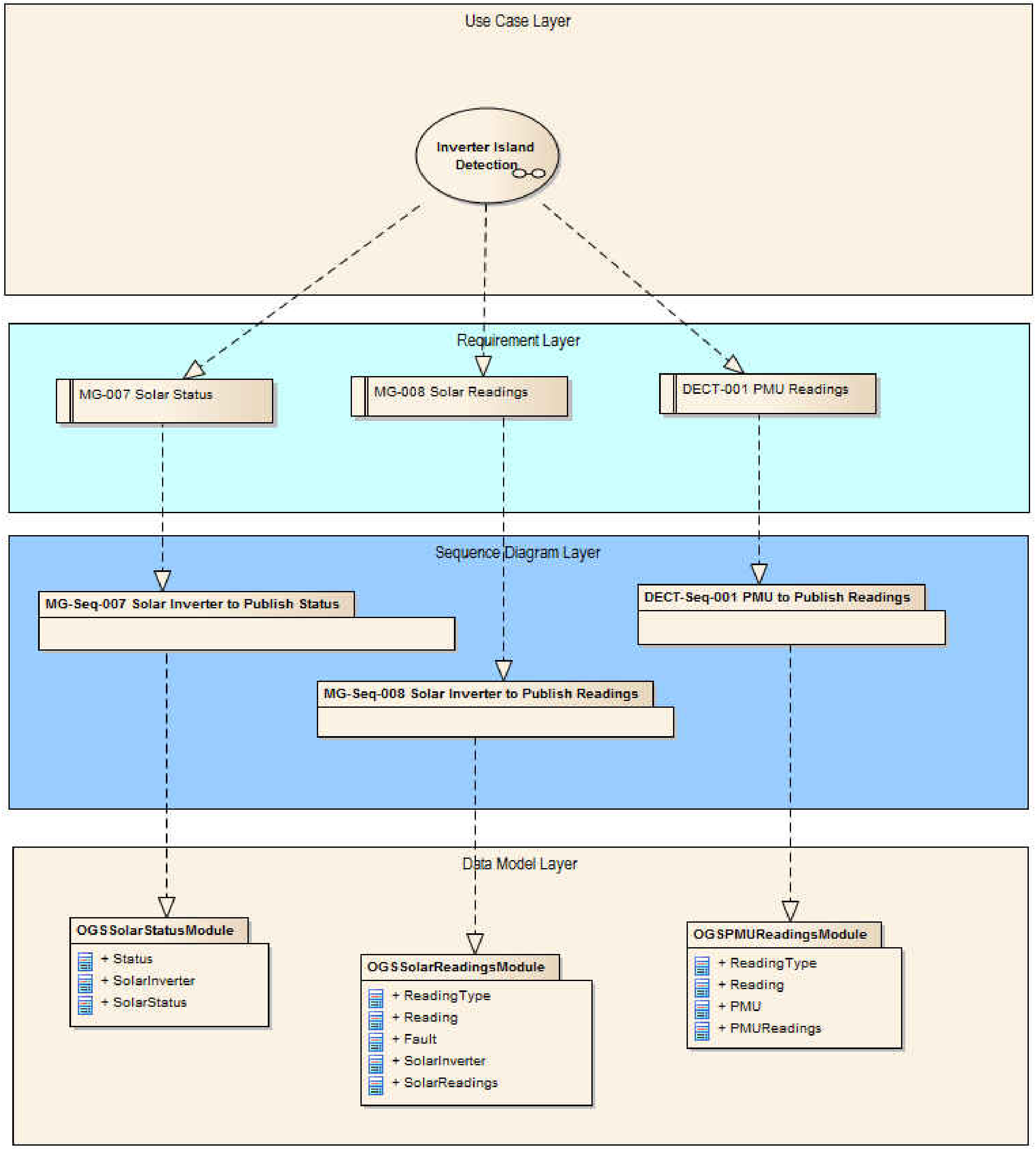


Figure 5-22: Top-level Business Model for the Inverter Island Detection Use-case

5.2.1.3 Use-case 3: FLISR

This subsection describes the process and overall details for the fault detection, isolation, sectionalization, and restoration (FLISR) application, which was the third use-case created using this interoperability framework at Duke Energy. Similar to the other 2 use-cases, the process contains an overview, diagrams for use-case, activity process and sequences, list of requirements, and top-level business model for FLISR.

As depicted in Figure 5-23, the recipe for FLISR includes a closed-loop control scheme with two breakers at the substation and 5 reclosers on the grid, where each breaker is normally closed to allow a separate feeder to be supplied load from the substation through two normally closed reclosers in series, but the ends of each feeder are connected to the same normally open tiepoint recloser, R3. In the event of a fault on the line between recloser R2 and recloser R5, the R2 and R5 will open, while R3 will close at the tie point to restore power from the Breaker B1 side until the back side of R5.

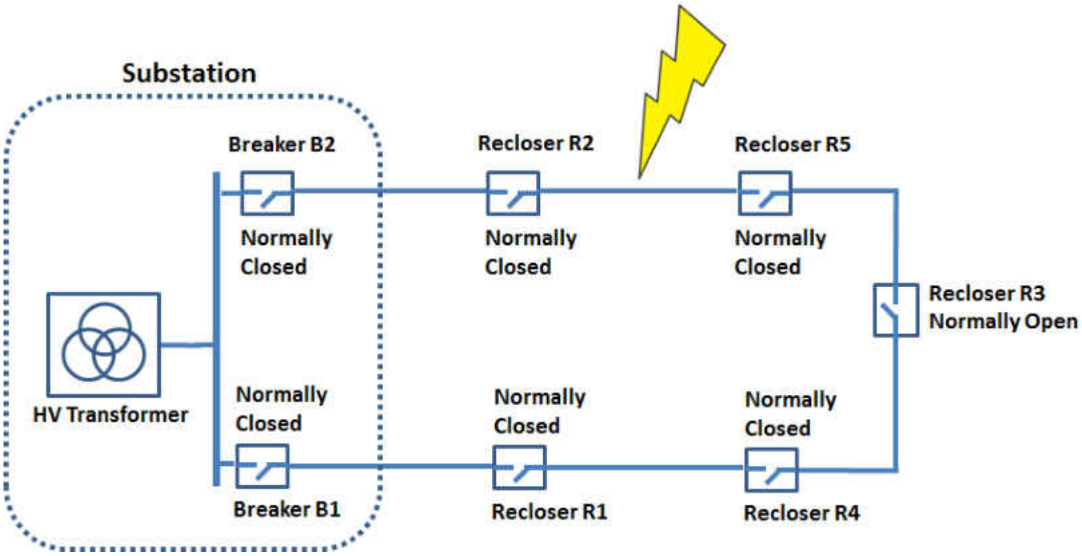


Figure 5-23: Overview of the FLISR Use-case Description

Based on the overall description of FLISR application provided above, the following use-case diagram was created in Figure 5-24. As illustrated below, the breaker, recloser, and DMS were identified as the actors, while being linked to the 4 different types of requirements.

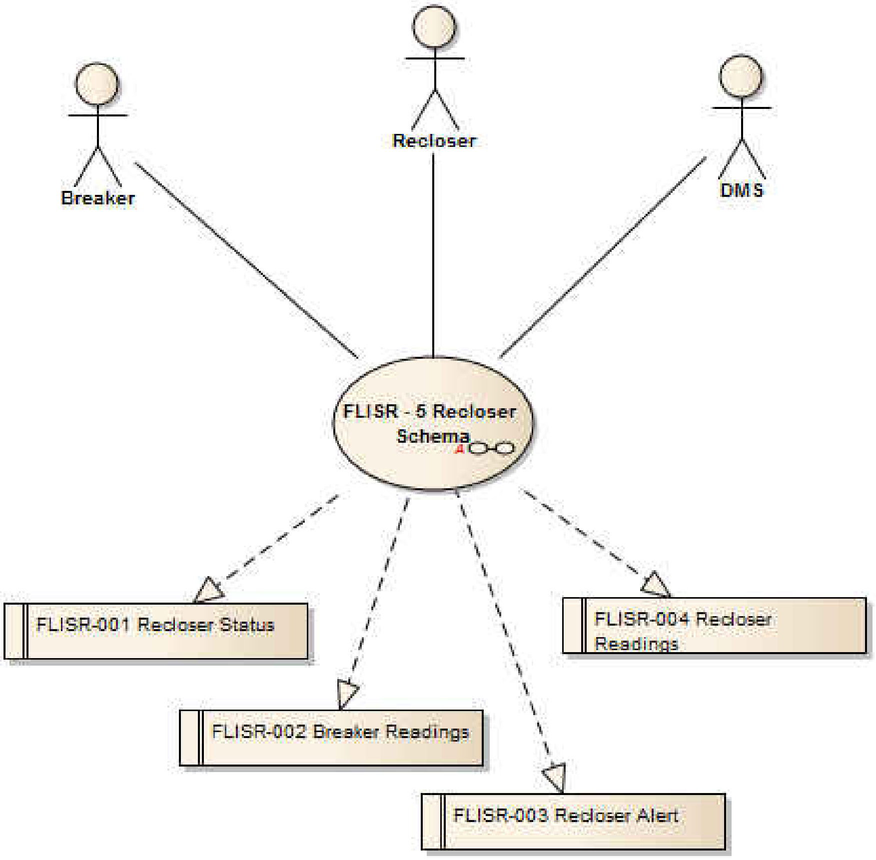
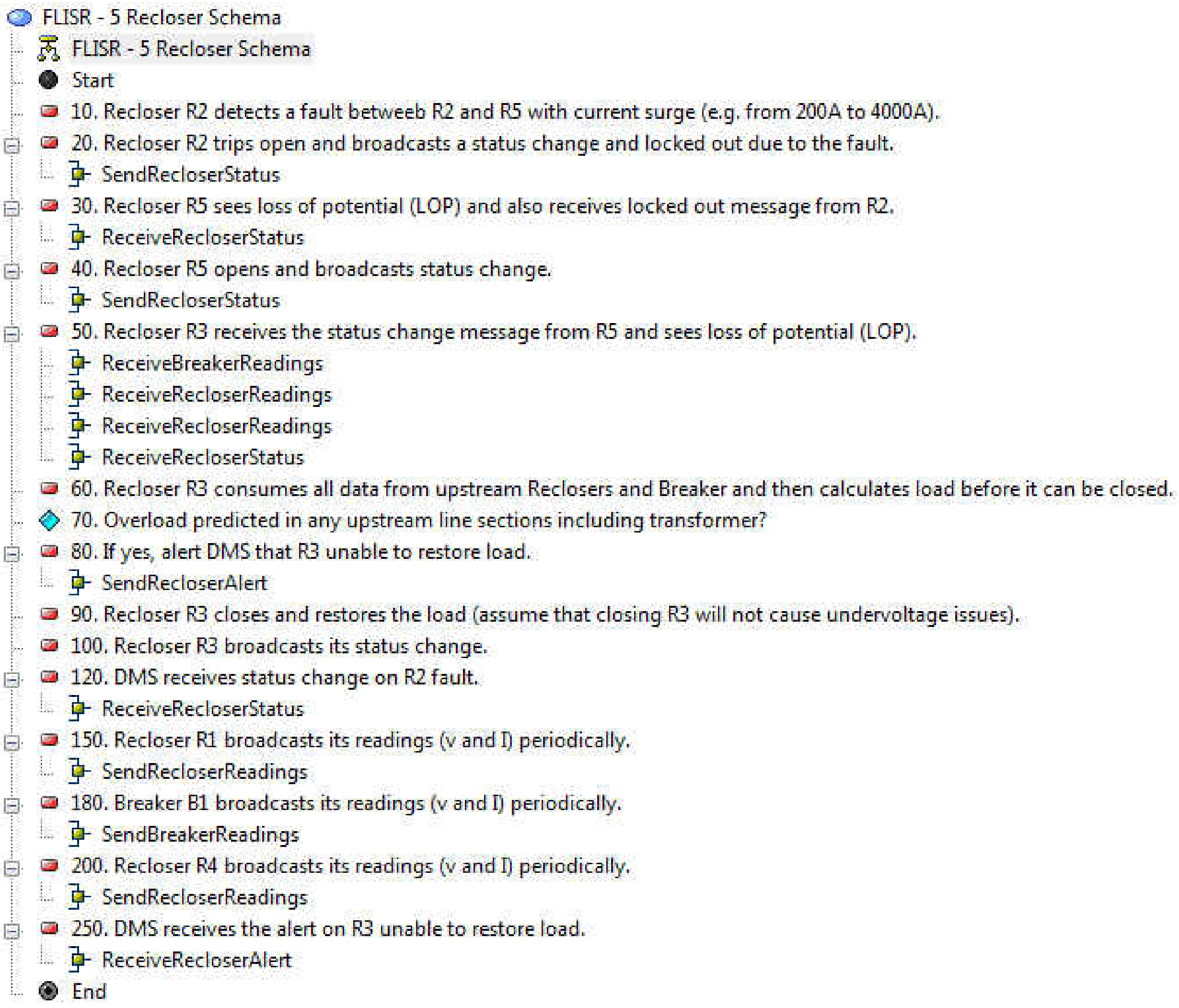


Figure 5-24: Use-case Diagram for the FLISR Application

Figure 5-25 on the next page shows the process for FLISR as a list of steps that includes the actions and commands, while Figure 5-26 on the following page provides the same process steps of this use-case activity in the form of an activity diagram. For the FLISR application, the first 2 steps, namely 10 and 20, are steps related to R2 detecting current surge and publishing fault status, while step 30 and 40 are related to R5 detecting a loss of potential, receiving message from R2, and publishing its own status. Steps 50, 60, 80, 90, and 100 are related to the tie-point R3 in receiving the breaker and recloser readings and status from others, while closing itself if the DMS approves, and broadcasting its status change. For step 120, DMS is updated, while for steps 150, 180, and 200, recloser R1, breaker B1, and recloser R4, respectively, publish data and steps 120 and 250 involved data updates being subscribed by DMS.



FLISR - 5 Recloser Schema
- FLISR - 5 Recloser Schema
- Start
- 10. Recloser R2 detects a fault betweeb R2 and R5 with current surge (e.g. from 200A to 4000A).
- 20. Recloser R2 trips open and broadcasts a status change and locked out due to the fault.
  - SendRecloserStatus
- 30. Recloser R5 sees loss of potential (LOP) and also receives locked out message from R2.
  - ReceiveRecloserStatus
- 40. Recloser R5 opens and broadcasts status change.
  - SendRecloserStatus
- 50. Recloser R3 receives the status change message from R5 and sees loss of potential (LOP).
  - ReceiveBreakerReadings
  - ReceiveRecloserReadings
  - ReceiveRecloserReadings
  - ReceiveRecloserStatus
- 60. Recloser R3 consumes all data from upstream Reclosers and Breaker and then calculates load before it can be closed.
- 70. Overload predicted in any upstream line sections including transformer?
- 80. If yes, alert DMS that R3 unable to restore load.
  - SendRecloserAlert
- 90. Recloser R3 closes and restores the load (assume that closing R3 will not cause undervoltage issues).
- 100. Recloser R3 broadcasts its status change.
- 120. DMS receives status change on R2 fault.
  - ReceiveRecloserStatus
- 150. Recloser R1 broadcasts its readings (v and I) periodically.
  - SendRecloserReadings
- 180. Breaker B1 broadcasts its readings (v and I) periodically.
  - SendBreakerReadings
- 200. Recloser R4 broadcasts its readings (v and I) periodically.
  - SendRecloserReadings
- 250. DMS receives the alert on R3 unable to restore load.
  - ReceiveRecloserAlert
- End

Figure 5-25: Activity Process List for the FLISR Use-case

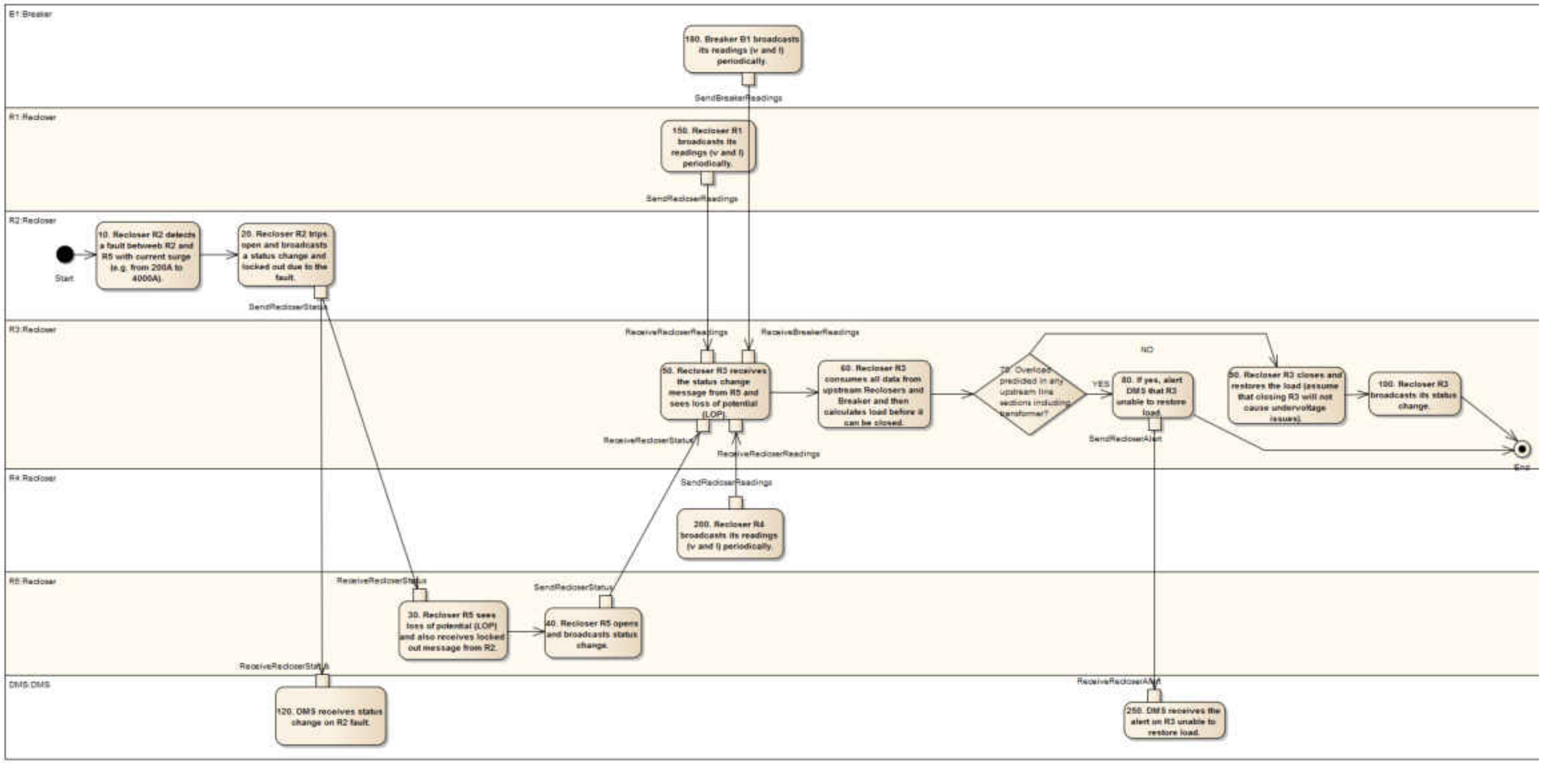


Figure 5-26: Activity Diagram for the FLISR Use-case

After the activity diagram was generated, the list of requirements was defined for the 4 functions highlighted and displayed below in Figure 5-27. Similar to the first use-case, each separate requirement had to be entered to describe the mandatory data fields for each function. For FLISR, an example screenshot from the properties tab of the recloser status requirement, showed in Figure 5-28, reveals the various data fields required for this use-case function, such as nominal state, current state, a lockout boolean, and a fault remark.

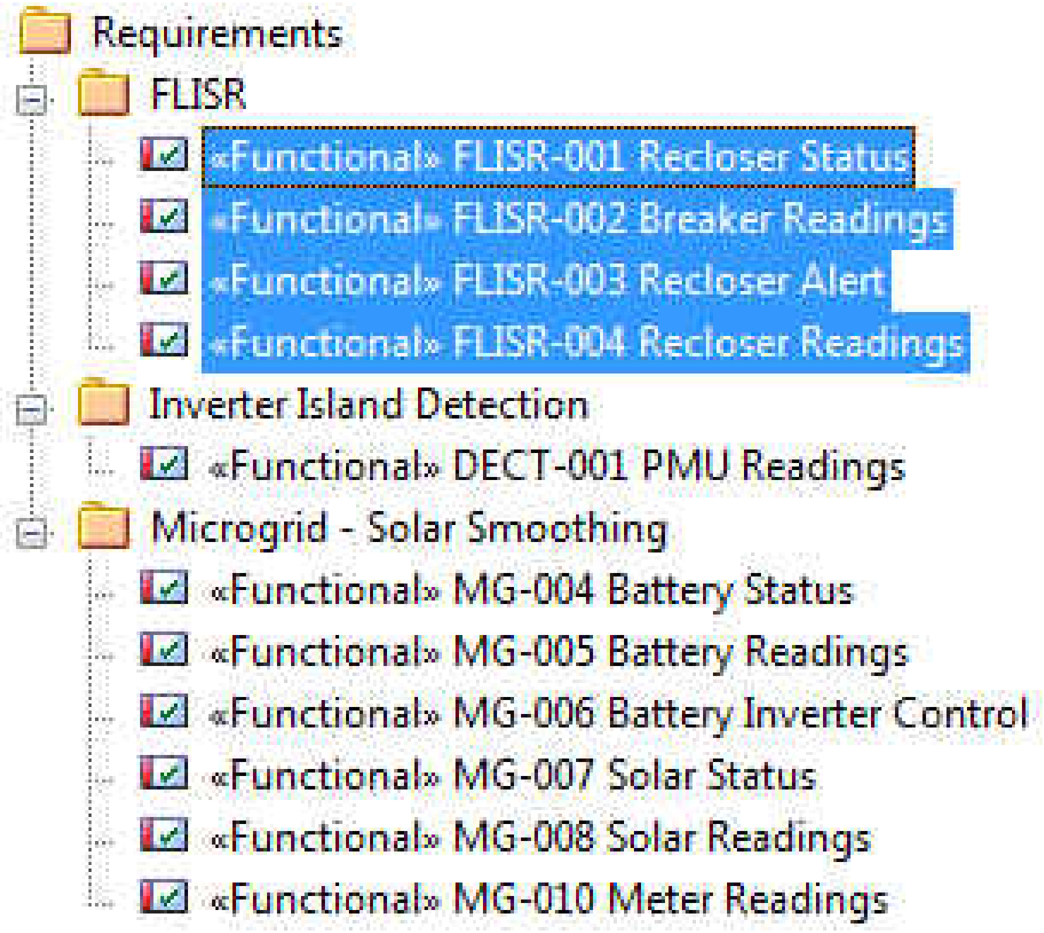
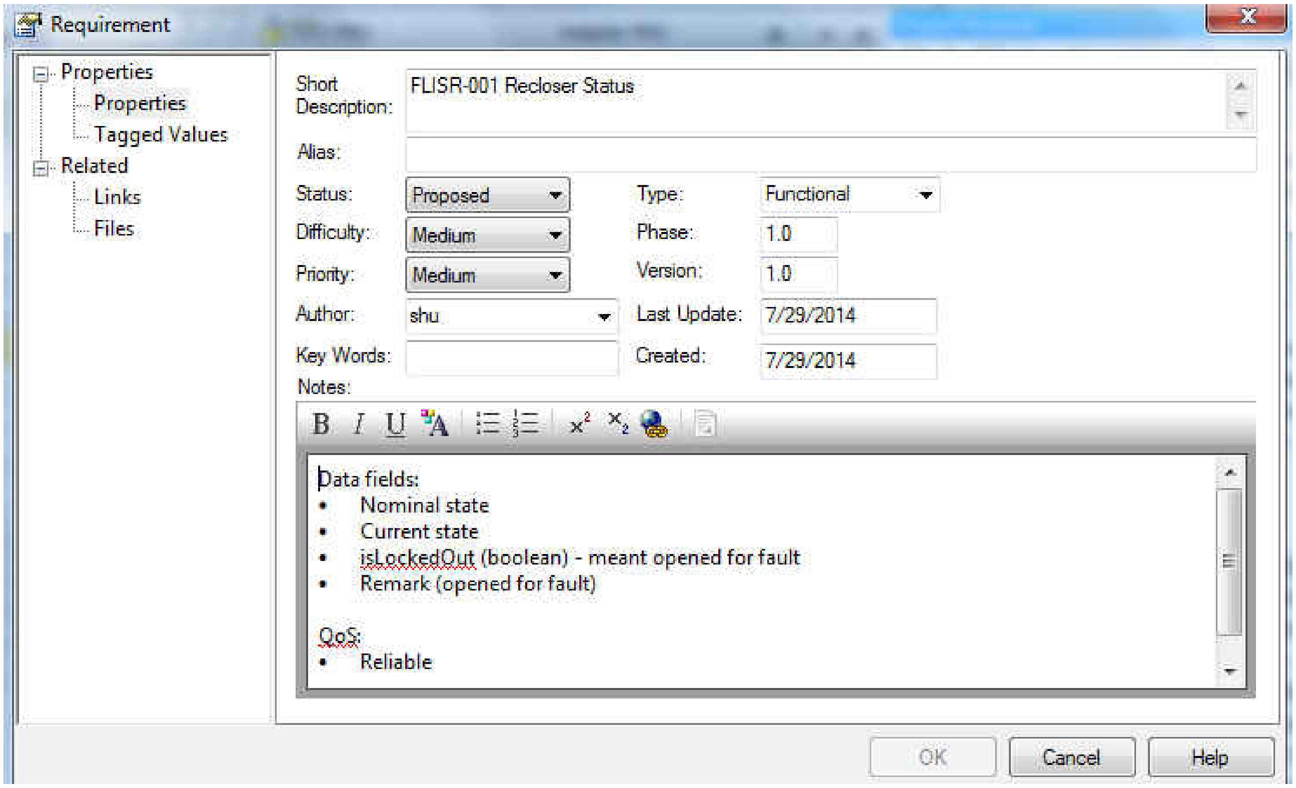

- Requirements
  - FLISR
    - «Functional» FLISR-001 Recloser Status
    - «Functional» FLISR-002 Breaker Readings
    - «Functional» FLISR-003 Recloser Alert
    - «Functional» FLISR-004 Recloser Readings
  - Inverter Island Detection
    - «Functional» DECT-001 PMU Readings
  - Microgrid - Solar Smoothing
    - «Functional» MG-004 Battery Status
    - «Functional» MG-005 Battery Readings
    - «Functional» MG-006 Battery Inverter Control
    - «Functional» MG-007 Solar Status
    - «Functional» MG-008 Solar Readings
    - «Functional» MG-010 Meter Readings

Figure 5-27: List of Requirements for FLISR



Short Description: FLISR-001 Recloser Status

Alias:

Status: Proposed

Type: Functional

Difficulty: Medium

Phase: 1.0

Priority: Medium

Version: 1.0

Author: shu

Last Update: 7/29/2014

Key Words:

Created: 7/29/2014

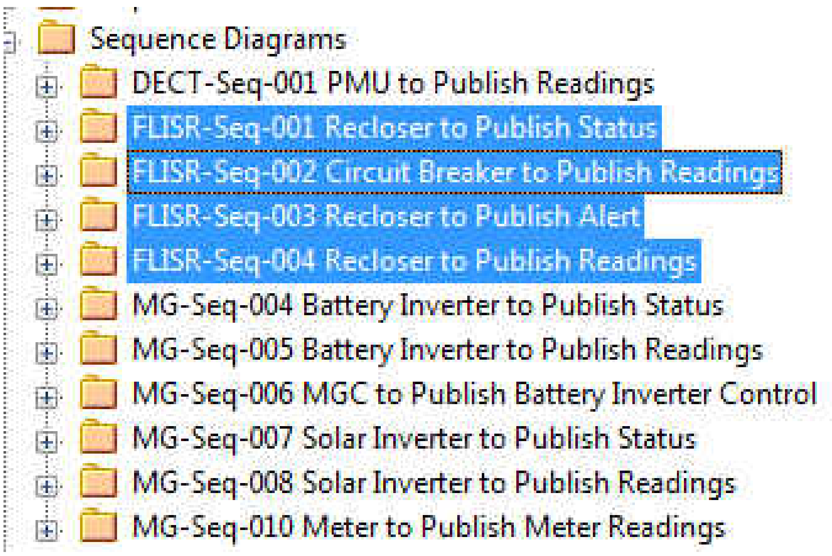
Notes:

Data fields:
- Nominal state
- Current state
- isLockedOut (boolean) - meant opened for fault
- Remark (opened for fault)

QoS:
- Reliable

Figure 5-28: Example Requirement Tab for the Battery Readings Function

After inputting and finalizing the various requirements of the 4 functions into EA, the sequence diagrams were next generated for this use-case in Figure 5-29. For FLISR, an example sequence diagram is represented for the circuit breaker to publish reading function in Figure 5-30. In this sequence diagram, the native format of the circuit breaker is converted to CIM DDS before being published to the FMB that is being subscribed to by the recloser adapter that translates it back to a legacy protocol, DNP.



Sequence Diagrams
DECT-Seq-001 PMU to Publish Readings
FLISR-Seq-001 Recloser to Publish Status
FLISR-Seq-002 Circuit Breaker to Publish Readings
FLISR-Seq-003 Recloser to Publish Alert
FLISR-Seq-004 Recloser to Publish Readings
MG-Seq-004 Battery Inverter to Publish Status
MG-Seq-005 Battery Inverter to Publish Readings
MG-Seq-006 MGC to Publish Battery Inverter Control
MG-Seq-007 Solar Inverter to Publish Status
MG-Seq-008 Solar Inverter to Publish Readings
MG-Seq-010 Meter to Publish Meter Readings

Figure 5-29: List of Sequence Diagrams for the FLISR Use-case

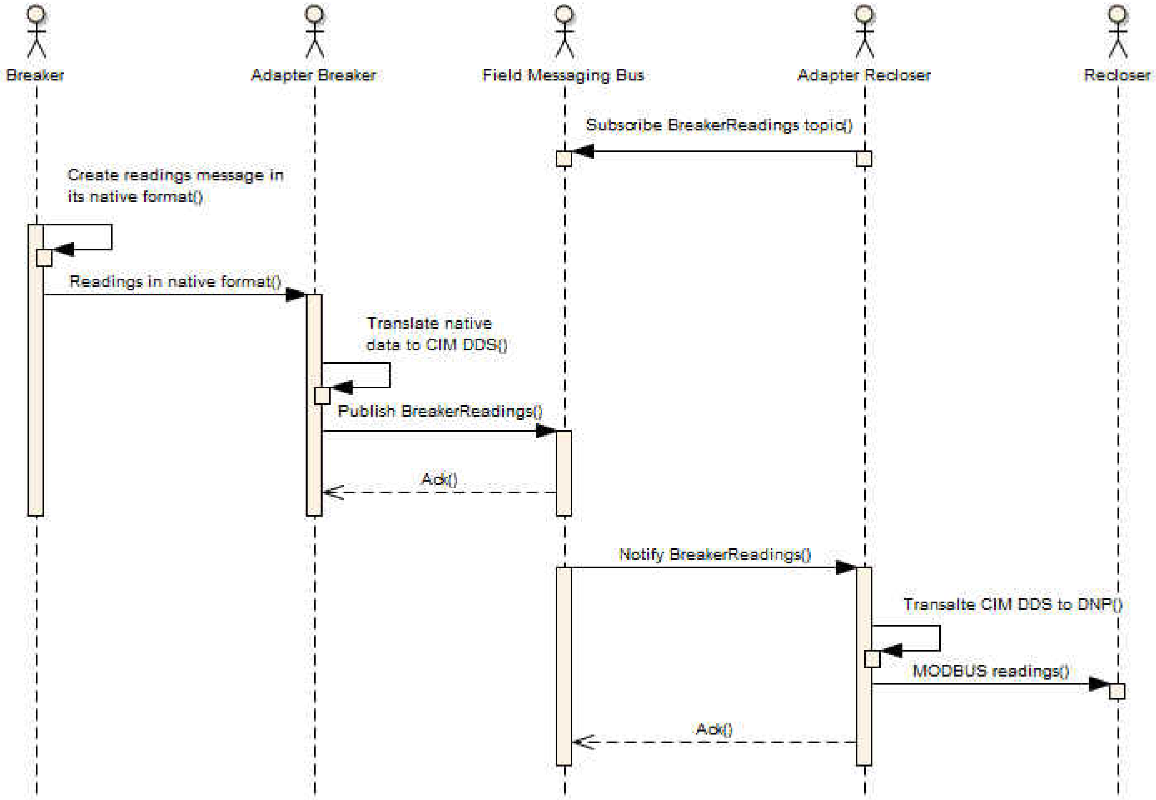


Figure 5-30: Example Sequence Diagram for Circuit Breaker to Publish Reading Action

Similar to the other two use-cases, the top-level business model for FLISR was produced in Figure 5-22. Section 5.2.2 will provide more detail on the data model layers and its reference profiles in UML.

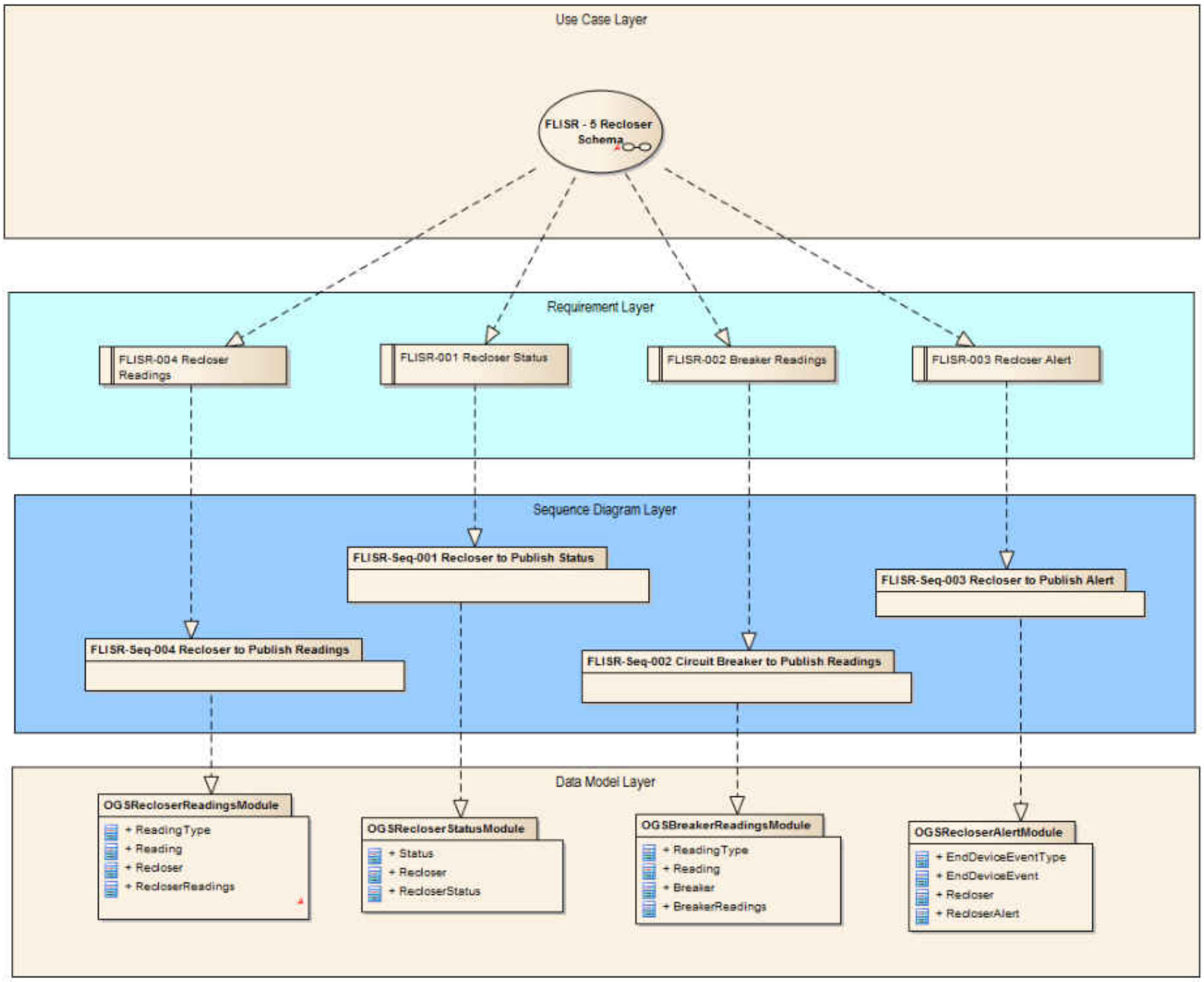


Figure 5-31: Top-level Business Model for the FLISR Use-case

5.2.2 Common Semantic Model Reference Standard

The second important step of the information modeling phase, within the use-case application framework, is identifying and referencing to an appropriate common semantic model standard. As illustrated above in the overall top-level business model diagrams for each use case, the bottom data model layer is the derived from the top three layers (use-case, requirements, and sequence diagram), but requires some parallel insight on which common semantic model artifact classes are available to descend from.

For this case study, the utility industry standard that was selected for the reference common semantic model was the Common Information Model (CIM) suite governed by the IEC Technical Committee 57 (TC57) Working group due to its comprehensive vocabulary breadth in the traditional electric grid power delivery infrastructure and also due to its availability in UML format, which aligns with the semantic context phase. This suite of CIM data models referenced for this case study was obtained by the CIM Users group, which is a subgroup of the Utility Communications Architecture International Users Group (UCAIug) that maintains a central repository of the utility taxonomies and interoperability data models standardized by the IEC TC57. Of the 3 IEC standard categories within CIM, only 2 of them, namely, IEC 61970 for transmission assets and IEC 61968 for distribution assets, were considered relevant and useful for this case study since the third one, IEC 62325 is focused on energy markets. Furthermore, as depicted in Figure 5-32, though the packages were designed for specific domains of the energy industry, there exists several different hierarchical relationships between them with IEC 61970 being the parent to both IEC 61968 and IEC 62325, while IEC 61968 can also a parent to IEC 62325. These relationships become imperative to remember in the contextual mapping phase, especially as many of the classes used in this case study, that is distribution grid focused, are referenced from IEC 61968, which inherits artifacts from IEC 61970.

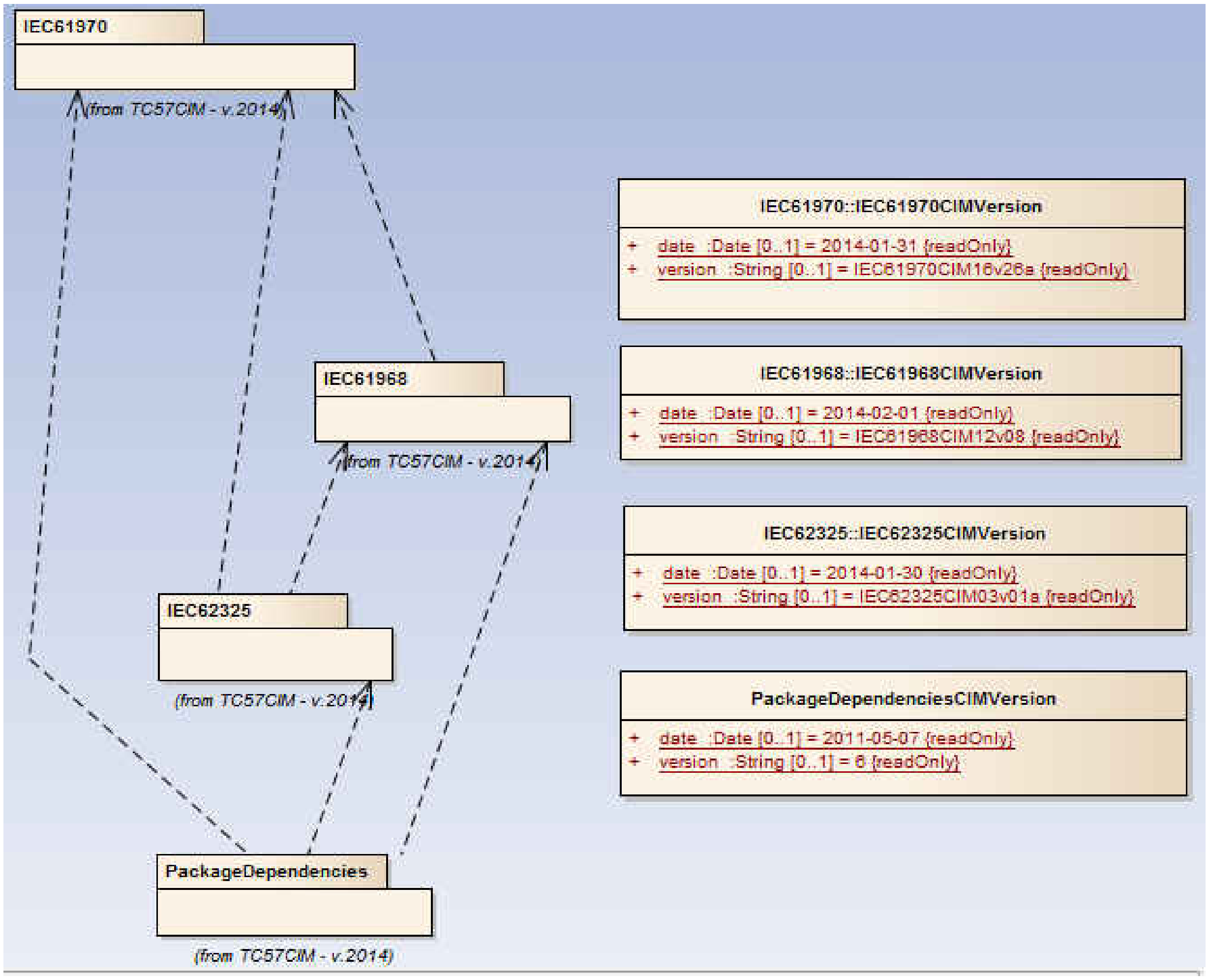


Figure 5-32: CIM TC57 Reference UML packages Obtained by the CIM Users Group

5.3 Semantic Context

After completion of the use-case requirements diagrams in a MBSE tool, such as EA, along with the selection of utility industry standardized common semantic model, the next phase of the use-case application framework for this case study consisted of generating the semantic context for each use-case. Though viewed as a single phase for this framework, this section is best described by including two subsections. The first part reveals the mapping process of the CIM reference profiles and the second part exhibits the developed UML profiles of the bottom data model layers that were illustrated in the overall top-level business models generated in the previous section.

5.3.1 CIM Reference Profile Mapping

Though the importing of CIM, based on IEC TC57 standard, to UML profiles could be done manually, a free add-in extension, known as CIM EA by Xtensible Solutions, was utilized to simplify and improve consistency during the mapping process to use-case specific UML profiles by automatically generating artifacts based on the CIM UML files that were imported from the UCAIug's CIM Users group. Additionally, another plug-in extension, known as Model Driven Information, Integration and Intelligence (MD3i) by Xtensible Solutions, that Duke Energy owned the license to, was found to be another useful mapping tool to facilitate the alignment, consistency, and traceability between the use-case requirement diagrams and the reference semantic models in CIM UML. Since the CIM suites, IEC 61970 and IEC 61968, are very comprehensive data models with several hierarchical levels that contain many optional artifacts, it can be overwhelming, tedious, and error-prone to sort through the various classes and datatypes to map the use-case requirements directly to the CIM-based UML profiles without any mismatches, typos, or redundant extensions. Another feature the MD3i platform brings is its ability to create and management an enterprise semantic base repository in the EA package that was easily ported and re-used across all use-cases, such as in the second use-case of inverter island detection that leveraged 2 building blocks, namely, solar status and solar reading, from the first use-case microgrid solar smoothing.

Before diving directly into the UML profiles for this case study, it is worth noting some of the example artifacts and classes from the reference standards. Figure 5-33 shows an example of the naming conventions from the parent IEC 61970 that is inherited throughout all the other reference models and this enterprise semantic base to be used for this case study. Additionally, Figures 5-34 and 5-35 provides examples of some common artifacts referenced in the IEC 61968 standard for EndDeviceControl and ReadingTypes classes, respectively, which came handy for each use-case's end device and their associated subordinate classes for controls and reading profiles. Furthermore, Figure 5-36 shows the enumeration artifacts that were referenced and re-used from IEC 61970's core folder for the PhaseCode data type and from IEC 61968's domain folder for the UnitSymbol and UnitMultipler data types.

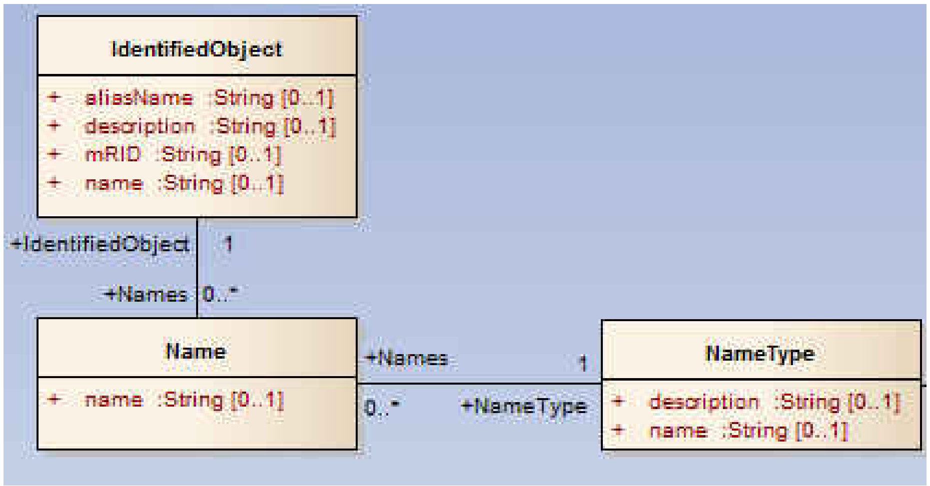


Figure 5-33: Naming Artifacts Referenced from the IEC 61970 Standard

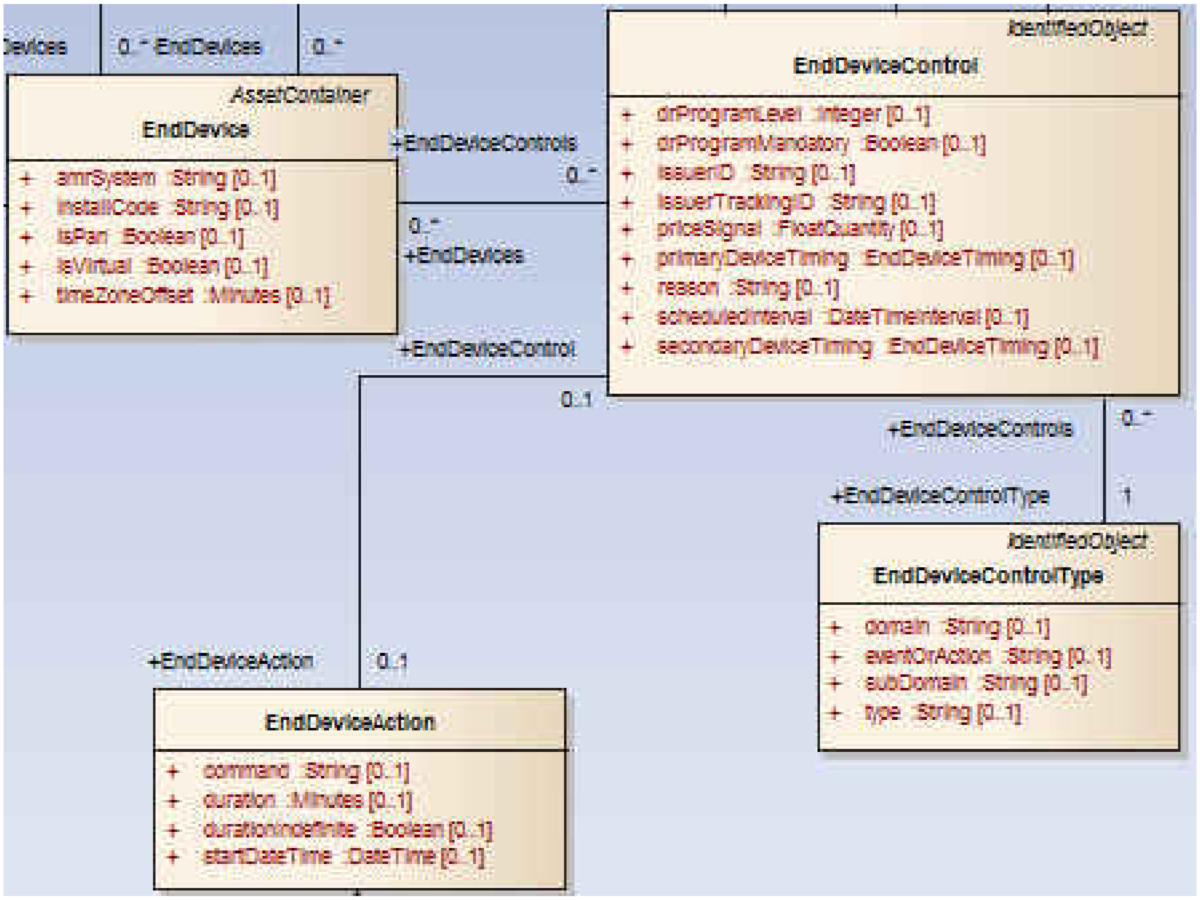


Figure 5-34: EndDeviceControl and Related Artifacts Referenced from the IEC 61968 Standard

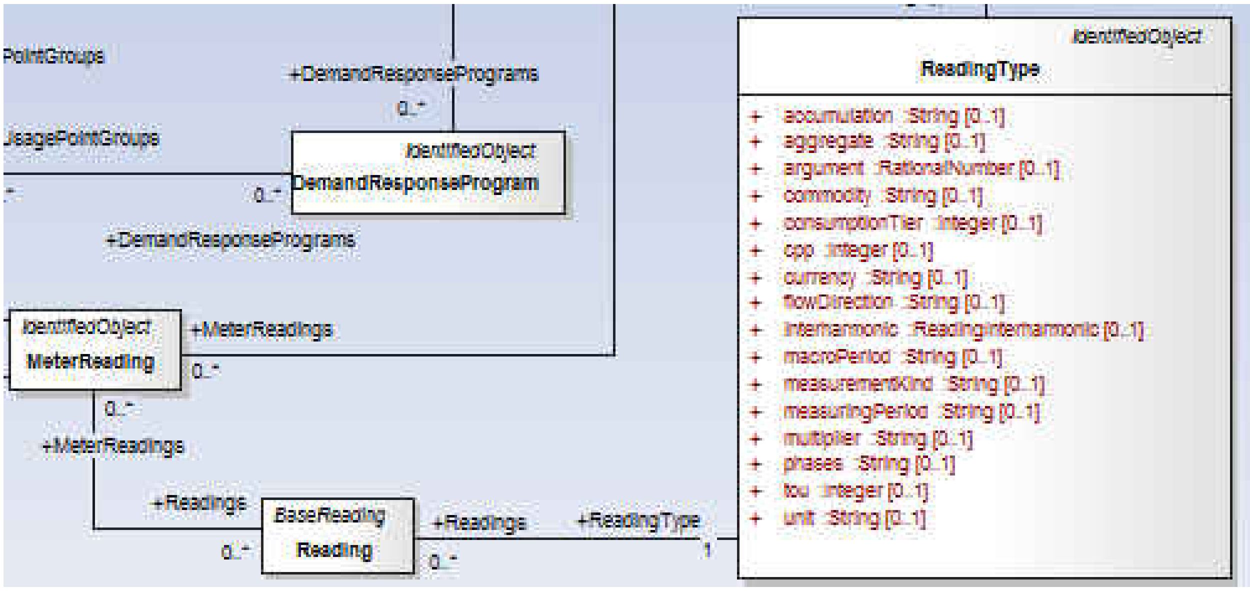


Figure 5-35: ReadingType and Related Artifacts Referenced from the IEC 61968 Standard

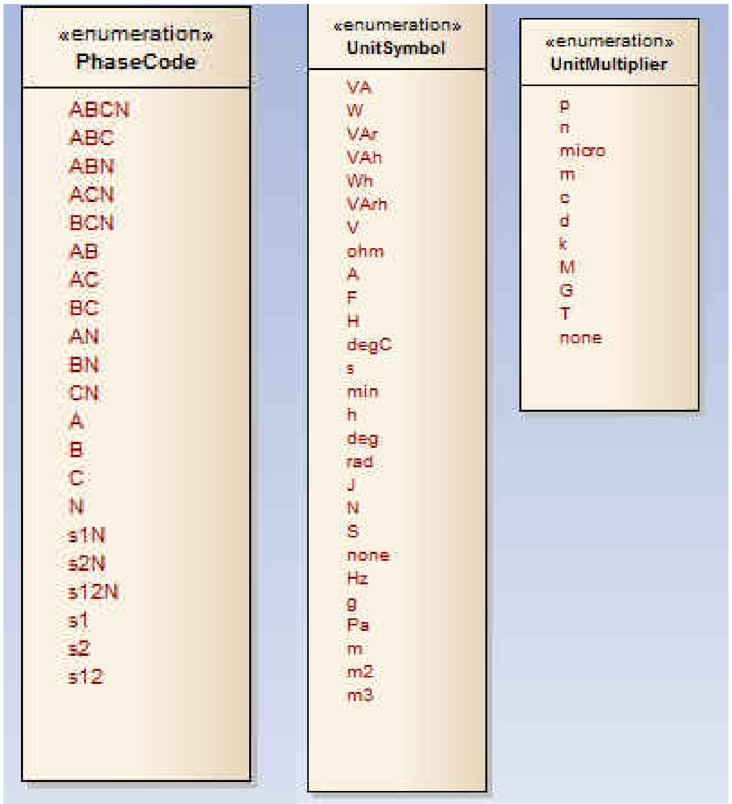


Figure 5-36: Enumeration Artifacts Referenced from the IEC 61970 and IEC 61968 Standards

5.3.2 UML Profiles

The subsection walks through the representative CIM-based UML profiles that were created for each requirement, or data model layer defined, in the three use-cases developed at Duke Energy. The goal of the UML profile is to provide the overarching semantic context for each function to be used throughout the enterprise semantic base. For this case study, since OMG's DDS message-oriented middleware is the desired standards-based wire protocol and API for interoperability between field devices and systems, the CIM-based data models in UML were implemented in its preferred and native schema format, IDL, which was derived from another OMG distributed object-oriented paradigm standard, known as Common Object Request Broker Architecture (CORBA). Figure 5-37, illustrates the final list of the 16 CIM-based UML profiles that were created as CORBA modules with the intent to later generate IDLs. One detail to note on the nomenclature for each module is the "OGS" appended to each one, which is short for the name of the repository for the demo, known as opengridstandards.

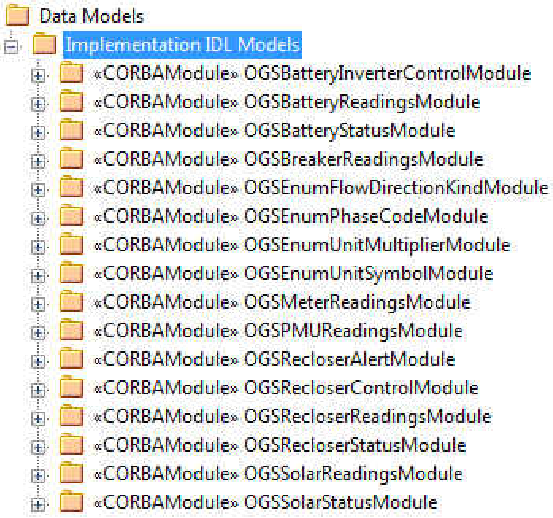
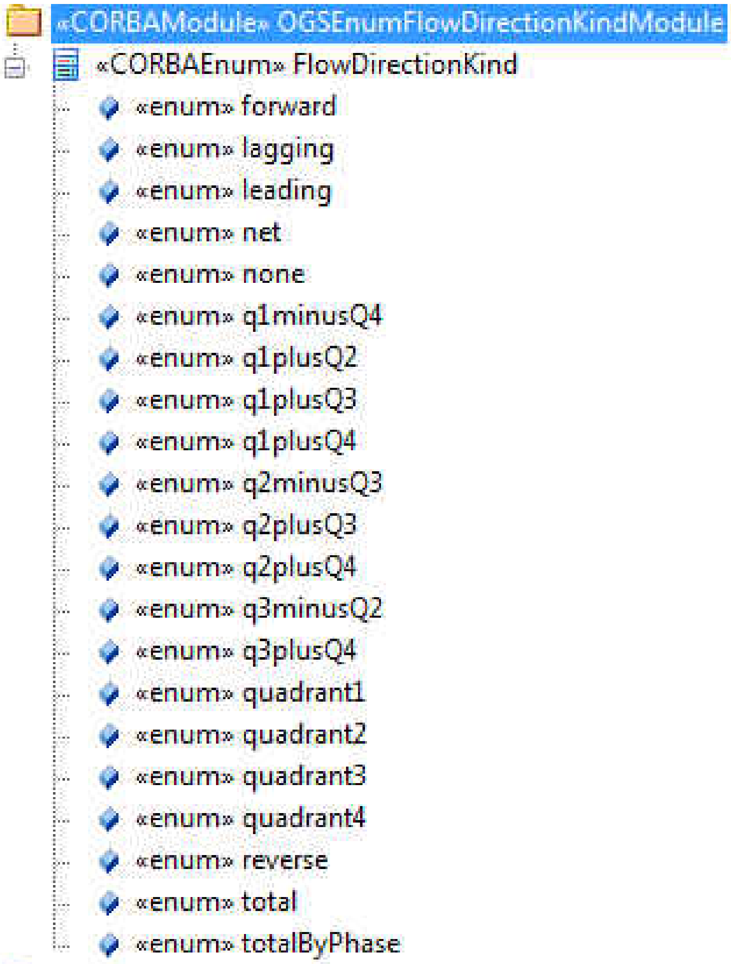

Data Models
Implementation IDL Models
«CORBAModule» OGSBatteryInverterControlModule
«CORBAModule» OGSBatteryReadingsModule
«CORBAModule» OGSBatteryStatusModule
«CORBAModule» OGSBreakerReadingsModule
«CORBAModule» OGSEnumFlowDirectionKindModule
«CORBAModule» OGSEnumPhaseCodeModule
«CORBAModule» OGSEnumUnitMultiplierModule
«CORBAModule» OGSEnumUnitSymbolModule
«CORBAModule» OGSMeterReadingsModule
«CORBAModule» OGSPMUReadingsModule
«CORBAModule» OGSRecloserAlertModule
«CORBAModule» OGSRecloserControlModule
«CORBAModule» OGSRecloserReadingsModule
«CORBAModule» OGSRecloserStatusModule
«CORBAModule» OGSSolarReadingsModule
«CORBAModule» OGSSolarStatusModule

Figure 5-37: List of CIM-based UML Profiles Generated for this Case Study

Another important detail to note about these profiles designed for IDL schemas is that this list of 16 elements, includes both the 12 functions defined in the bottom data model layer of the top-level overall business model in the use-case requirements phase, depicted previously in Figure 5-3, and the 4 functions that model the enumeration data types, namely the FlowDirectionKind, PhaseCode, UnitMultiplier, and UnitSymbol. Incidentally, of the 4 enumeration data types, only the FlowDirectionKind required a model extension as shown in Figure 5-38, while the other 3 ones were re-used directly from the CIM TC57 reference standards as shown previously in Figure 5-36.



«CORBAModule» OGSEnumFlowDirectionKindModule
«CORBAEnum» FlowDirectionKind
«enum» forward
«enum» lagging
«enum» leading
«enum» net
«enum» none
«enum» q1minusQ4
«enum» q1plusQ2
«enum» q1plusQ3
«enum» q1plusQ4
«enum» q2minusQ3
«enum» q2plusQ3
«enum» q2plusQ4
«enum» q3minusQ2
«enum» q3plusQ4
«enum» quadrant1
«enum» quadrant2
«enum» quadrant3
«enum» quadrant4
«enum» reverse
«enum» total
«enum» totalByPhase

Figure 5-38: Enumeration Artifacts Created for the FlowDirectionKind Extension

The remainder of this subsection will expose the 12 CIM-based UML profiles, in a CORBA Structure or IDL format, for the various functions of the meter, recloser, battery inverter, solar inverter, and phasor measurement unit (PMU). Given that all 5 of these end devices measure data and have publishing capabilities, the first 5 data models exhibited below are the Readings modules for them. With the exception of the meter, which decouples the EndDevice class from the Reading class as defined by TC57 standard, the remaining 4 power distribution asset devices have the same hierarchical relationships consisting of the same EndDeviceReadings, EndDevice, Reading, and ReadingType class building blocks. As shown below in Figures 5-39, 5-40, 5-41, 5-42, and 5-43, the ReadingType attributes are the same for end device, except for the PMU, which does not require a FlowDirection. The only other subtle difference between the 5 end devices of this type of CIM-based UML profile is the additional class extended to the solar inverter for the fault condition.

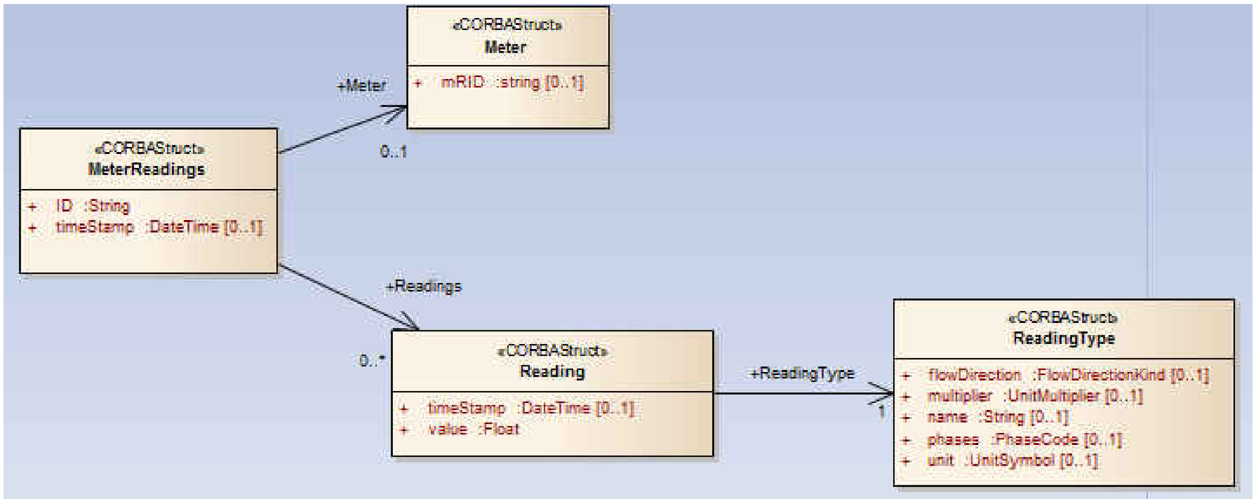


Figure 5-39: CIM-based UML Profile for MeterReadings Module

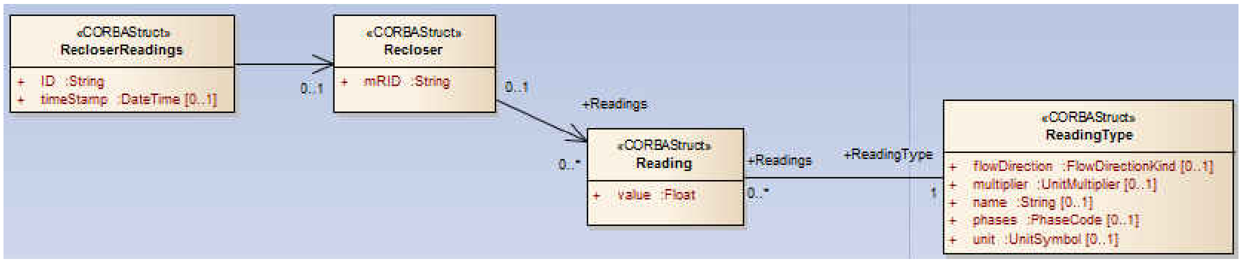


Figure 5-40: CIM-based UML Profile for RecloserReadings Module

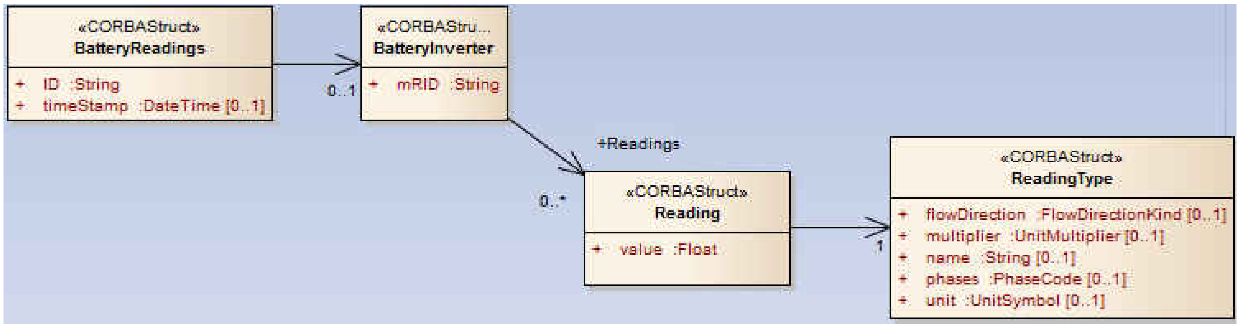


Figure 5-41: CIM-based UML Profile for BatteryReadings Module

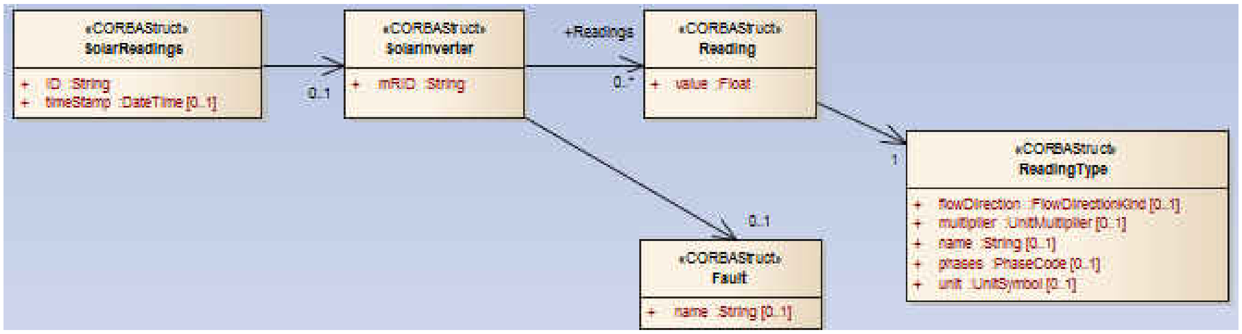


Figure 5-42: CIM-based UML Profile for SolarReadings Module

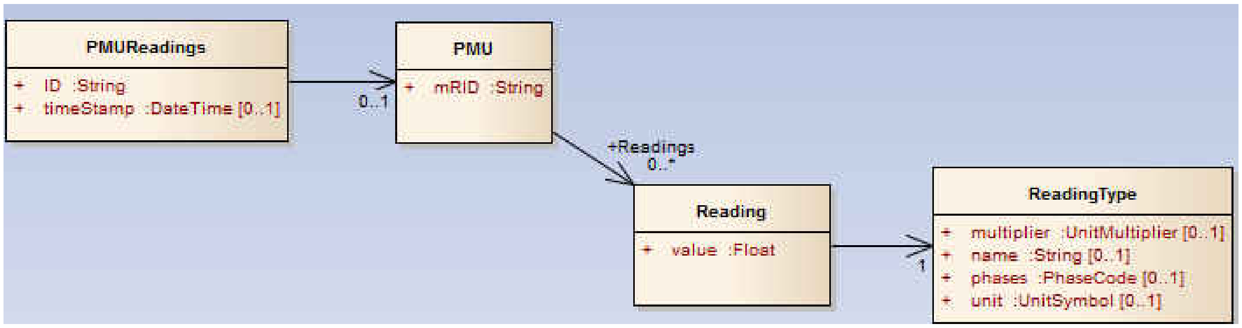


Figure 5-43: CIM-based UML Profile for PMUReadings Module

The next 2 data models below, in Figures 5-44 and 5-45, represent the control function modules from the battery inverter and recloser, respectively. With the exception of the SetPoint extension to the BatteryInverterControl module, the RecloserControl has essentially the same subclasses and attributes for the EndDeviceControl artifact.

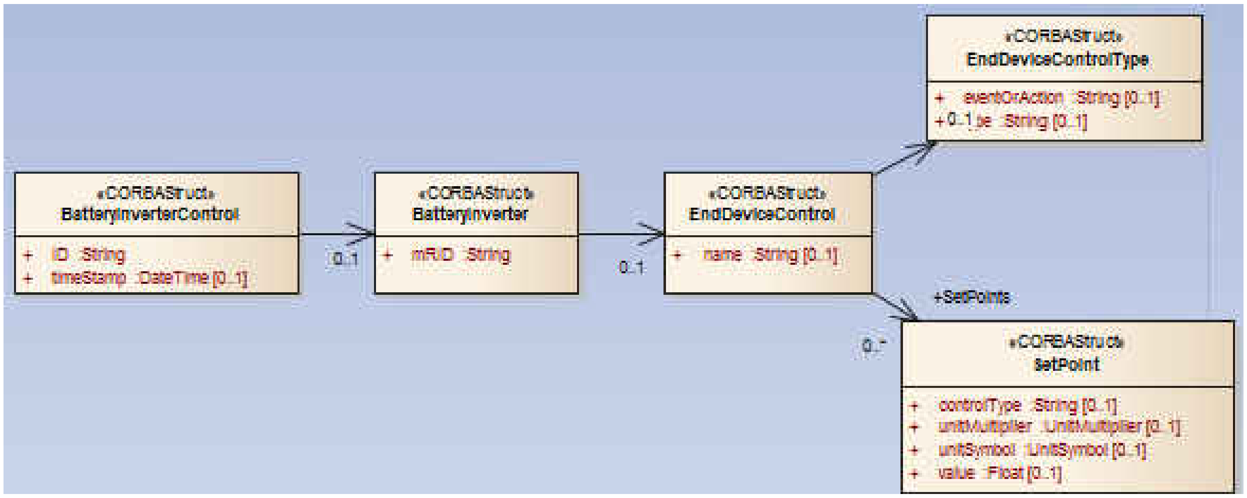


Figure 5-44: CIM-based UML Profile for BatteryInverterControl Module

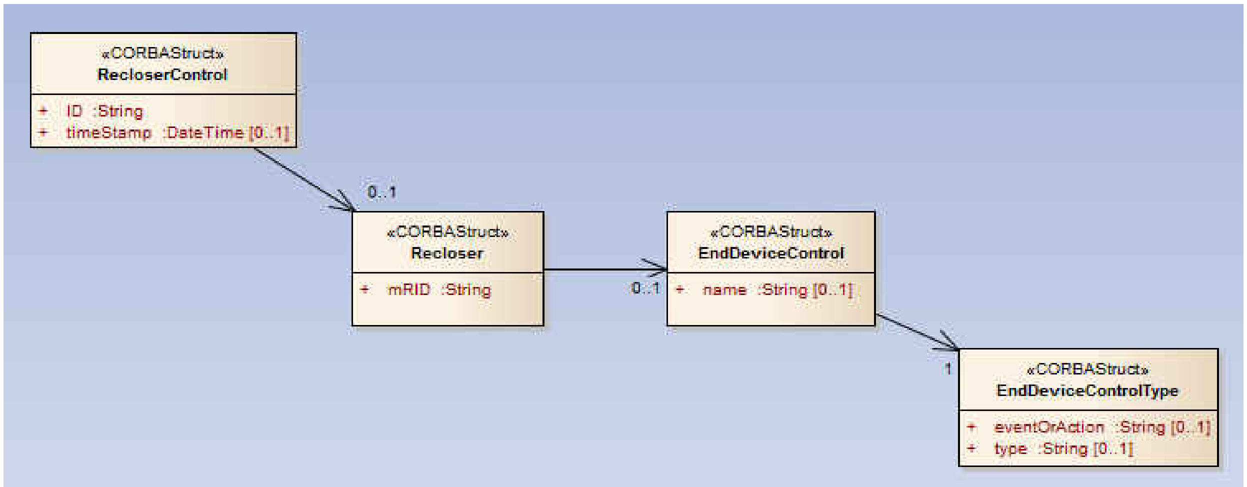


Figure 5-45: CIM-based UML Profile for RecloserControl Module

Unlike the other modules, the RecloserAlert module, shown in Figure 5-46, utilizes the EndDeviceEvent and EndDeviceEventType classes for its profile. As for the last 3 data models, displayed in Figures 5-47, 5-48, and 5-49, they represent the classes for the status reporting of the battery inverter, recloser, and solar inverters.

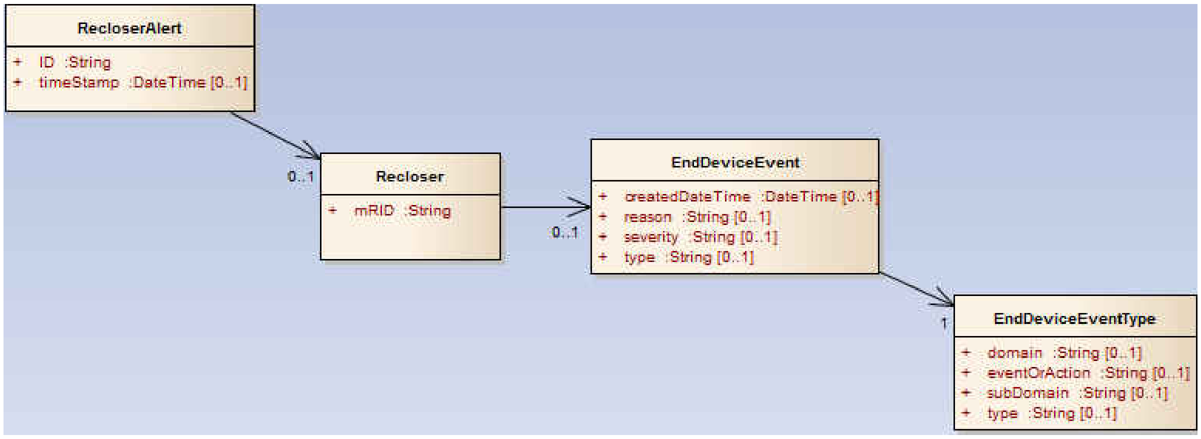


Figure 5-46: CIM-based UML Profile for RecloserAlert Module

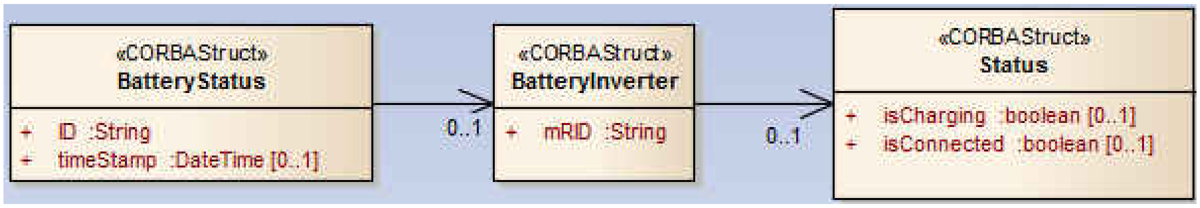


Figure 5-47: CIM-based UML Profile for BatteryStatus Module

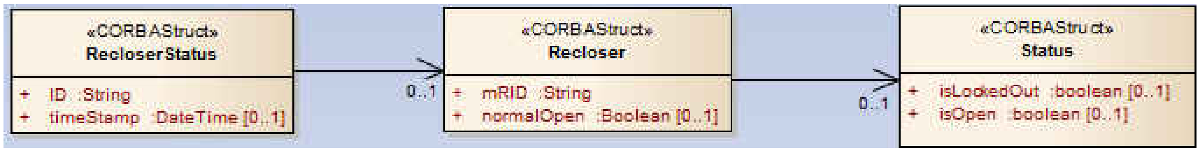


Figure 5-48: CIM-based UML Profile for RecloserStatus module

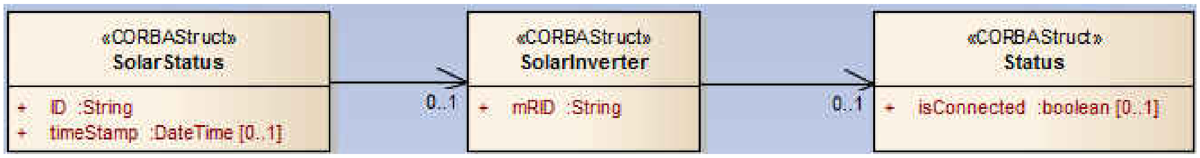


Figure 5-49: CIM-based UML Profile for SolarStatus Module

5.4 Message Syntax

Upon completion of CIM-based UML profiles for the 3 use-cases in this case study, the semantic context can be transformed into a message syntax that is first in a schema metadata format, then followed by code generation into a programming language, that is binary or text-based. The first subsection walks through the process of generating the schema in IDL and XSD formats, while the second subsection briefly describes the code generation process and the selected programming languages in java and XML.

5.4.1 Schema

One of the advantages of utilizing MBSE tools, like EA, is that there are so many options for using add-ins or plug-in extensions that can automatically generate UML to IDL or XSD. Alternatively, the DDS vendor implementations have professional modeling tools as part of their license fee that can generate IDLs from either XSD or UML. Within the EA offerings on the Sparx System's website, there are 2 different offerings from Model Driven Generation (MDG) Technologies: a free add-in, known as EA CORBA, that generates IDL's and a professional license version for DDS that generates IDLs and code in C, C++, C#, and java for the OMG standard DCPS and RTPS API's for both Real-time Innovation (RTI) ConnextDDS and Prismtech's OpenSpliceDDS implementations. For this case study, Duke Energy used the free EA CORBA add-in by MDG Technologies to generate the IDL schema and also took advantage of the automatic built-in UML to XSD generator within EA for the XSDs.

However, in order to ensure that the UML profiles converted properly to XSD, each of the 16 profiles in the data model layer had to have the <CORBAStruct> identifier removed from each class in the profiles.

Upon successful execution of the EA transformation tools and add-ins, the IDL and XSD files were generated for this case study and can be found in the Appendix. In order to illustrate an example schema for the BatteryInverterControl module, the IDL metadata is depicted in Table 5-1, while the XSD metadata is spread across two pages on Tables 5-2 and 5-3.

Table 5-1: IDL Schema for the BatteryInverterControl Module

```
#include <OGSEnumUnitMultiplier.idl>
#include <OGSEnumUnitSymbol.idl>

module OGSBatteryInverterControlModule
{
        struct EndDeviceControlType
        {
                String type;
        };
        struct SetPoint
        {
                String controlType;
                OGSEnumUnitMultiplierModule::UnitMultiplier unitMultiplier;
                OGSEnumUnitSymbolModule::UnitSymbol unitSymbol;
                Float value;
        };
        struct EndDeviceControl
        {
                String name;
                EndDeviceControlType EndDeviceControlType;
                sequence<SetPoint> SetPoints;
        };
        struct BatteryInverter
        {
                String mRID;
                EndDeviceControl EndDeviceControl;
        };
        struct BatteryInverterControl
        {
                String ID;
                DDS::Time_t timeStamp;
                BatteryInverter BatteryInverter;
        };
#pragma keylist BatteryInverterControl ID
};
```

Table 5-2: XSD Schema for the BatteryInverterControl Module (First Part)

```
<?xml version="1.0" encoding="utf-8"?>
<xs:schema xmlns:m="http://opengridstandards.org/xsd/2014/11/OGSBatteryInverterControlModule.xsd"
xmlns:xs="http://www.w3.org/2001/XMLSchema"
targetNamespace="http://opengridstandards.org/xsd/2014/11/OGSBatteryInverterControlModule.xsd" elementFormDefault="qualified"
attributeFormDefault="unqualified" version="1.0">
	<xs:element name="BatteryInverterControl" type="m:BatteryInverterControl"/>
	<xs:complexType name="BatteryInverter">
		<xs:sequence>
			<xs:element name="mRID" type="m:String"/>
			<xs:element name="EndDeviceControl" type="m:EndDeviceControl" minOccurs="0"/>
		</xs:sequence>
	</xs:complexType>
	<xs:complexType name="BatteryInverterControl">
		<xs:sequence>
			<xs:element name="ID" type="m:String"/>
			<xs:element name="timeStamp" type="m:DateTime" minOccurs="0"/>
			<xs:element name="BatteryInverter" type="m:BatteryInverter" minOccurs="0"/>
		</xs:sequence>
	</xs:complexType>
	<xs:simpleType name="DateTime">
		<xs:restriction base="xs:dateTime"/>
	</xs:simpleType>
	<xs:complexType name="EndDeviceControl">
		<xs:sequence>
			<xs:element name="name" type="m:String" minOccurs="0"/>
			<xs:element name="EndDeviceControlType" type="m:EndDeviceControlType"/>
			<xs:element name="SetPoints" type="m:SetPoint" minOccurs="0" maxOccurs="unbounded"/>
		</xs:sequence>
	</xs:complexType>
	<xs:complexType name="EndDeviceControlType">
		<xs:sequence>
			<xs:element name="eventOrAction" type="m:String" minOccurs="0"/>
			<xs:element name="type" type="m:String" minOccurs="0"/>
		</xs:sequence>
	</xs:complexType>
	<xs:simpleType name="Float">
		<xs:restriction base="xs:float"/>
	</xs:simpleType>
	<xs:complexType name="SetPoint">
		<xs:sequence>
			<xs:element name="controlType" type="m:String" minOccurs="0"/>
			<xs:element name="unit" type="m:UnitSymbol" minOccurs="0"/>
			<xs:element name="unitMultiplier" type="m:UnitMultiplier" minOccurs="0"/>
			<xs:element name="value" type="m:Float" minOccurs="0"/>
		</xs:sequence>
	</xs:complexType>
	<xs:simpleType name="String">
		<xs:restriction base="xs:string"/>
	</xs:simpleType>
	<xs:simpleType name="UnitMultiplier">
		<xs:restriction base="xs:normalizedString">
			<xs:enumeration value="c"/>
			<xs:enumeration value="d"/>
			<xs:enumeration value="G"/>
			<xs:enumeration value="k"/>
			<xs:enumeration value="M"/>
			<xs:enumeration value="m"/>
			<xs:enumeration value="micro"/>
			<xs:enumeration value="n"/>
			<xs:enumeration value="none"/>
```

Table 5-3: XSD Schema Con't for the BatteryInverterControl Module (Second Part)

```
                        <xs:enumeration value="p"/>
                        <xs:enumeration value="T"/>
                </xs:restriction>
        </xs:simpleType>
        <xs:simpleType name="UnitSymbol">
                <xs:restriction base="xs:normalizedString">
                        <xs:enumeration value="A"/>
                        <xs:enumeration value="deg"/>
                        <xs:enumeration value="degC"/>
                        <xs:enumeration value="F"/>
                        <xs:enumeration value="g"/>
                        <xs:enumeration value="h"/>
                        <xs:enumeration value="H"/>
                        <xs:enumeration value="Hz"/>
                        <xs:enumeration value="J"/>
                        <xs:enumeration value="m"/>
                        <xs:enumeration value="m2"/>
                        <xs:enumeration value="m3"/>
                        <xs:enumeration value="min"/>
                        <xs:enumeration value="N"/>
                        <xs:enumeration value="none"/>
                        <xs:enumeration value="ohm"/>
                        <xs:enumeration value="Pa"/>
                        <xs:enumeration value="rad"/>
                        <xs:enumeration value="S"/>
                        <xs:enumeration value="s"/>
                        <xs:enumeration value="V"/>
                        <xs:enumeration value="VA"/>
                        <xs:enumeration value="VAh"/>
                        <xs:enumeration value="VAr"/>
                        <xs:enumeration value="VArh"/>
                        <xs:enumeration value="W"/>
                        <xs:enumeration value="Wh"/>
                </xs:restriction>
        </xs:simpleType>
</xs:schema>
```

When visually comparing the two different schemas, it is clear that the IDL format is much leaner than XSD in terms of lines of text and is one of the reasons for it being the preferred format for DDS to compile with. The main reason for this simplicity is the enumeration superclasses that are appended at the top of the IDL, while the XSD metadata becomes much heavier since it embeds each enumeration structure and its corresponding list of data types.

5.4.2 Code Generation

Once the schema syntax in IDL and XSD formats is created from EA or another MBSE tool, the code generation to the popular programming language standards is fairly simple. For this case study, the code generation of XML text-based representations of topics, needed for MQTT, is an automatic function applied to the XSD schema file in the open-source eclipse web tools platform. For the DDS topics that are generated in a binary format, the eclipse platform will need to run the IDL preprocessor (idlpp) function using OpenSpliceDDS to generate the java classes, or C, C+, or C++ files. Figure 5-50 shows a screenshot of the java classes that were generated from the OpenSpliceDDS toolkit for the OGSBatteryStatusModule IDL file.

- OGSBatteryStatusModule
  - BatteryInverter.java
  - BatteryInverterHolder.java
  - BatteryStatus.java
  - BatteryStatusDataReader.java
  - BatteryStatusDataReaderHelper.java
  - BatteryStatusDataReaderHolder.java
  - BatteryStatusDataReaderImpl.java
  - BatteryStatusDataReaderOperations.java
  - BatteryStatusDataReaderView.java
  - BatteryStatusDataReaderViewHelper.java
  - BatteryStatusDataReaderViewHolder.java
  - BatteryStatusDataReaderViewImpl.java
  - BatteryStatusDataReaderViewOperations.java
  - BatteryStatusDataWriter.java
  - BatteryStatusDataWriterHelper.java
  - BatteryStatusDataWriterHolder.java
  - BatteryStatusDataWriterImpl.java
  - BatteryStatusDataWriterOperations.java
  - BatteryStatusHolder.java
  - BatteryStatusMetaHolder.java
  - BatteryStatusSeqHolder.java
  - BatteryStatusTypeSupport.java
  - BatteryStatusTypeSupportHelper.java
  - BatteryStatusTypeSupportHolder.java
  - BatteryStatusTypeSupportOperations.java
  - Status.java
  - StatusHolder.java

Figure 5-50: Screenshot of Java Classes Generated from the BatteryStatusModule IDL File

5.5 Message-Oriented Middleware Demonstration

After the java code and XML have been compiled by the message-oriented middleware implementations to create the CIM-based topics in DDS and MQTT, a technical verification for interoperability can be simulated by devising a simple technology-based field message bus demonstration using embedded M2M telemetry nodes and a web user interface. The following section highlights the details of the configuration setup and the output results of the field message bus demonstration.

5.5.1 Demo Configuration

In order to create a rapid prototype and easy-to-use system that can effectively verify and validate interoperability of the implemented framework at Duke Energy, the following configuration setup in Figure 5-51 was devised for the first use-case microgrid solar smoothing. As shown, there are 4 main categories of components in the demo, consisting of the input data sets for the end devices and use-case application logic, the M2M devices for each node that contains the IDL's, java compiler, and the selected open-source DDS middleware implementation, the DDS field message bus topics, and the text-based message interfaces that contains a node with DDS, java compiler, XSD's, XML, and MQTT, a cloud site with a MQTT broker, and a website, known as opergridstandards.org, that has a built-in public user interface, which automatically subscribes to and displays the real-time messages on the DDS data space in XML.

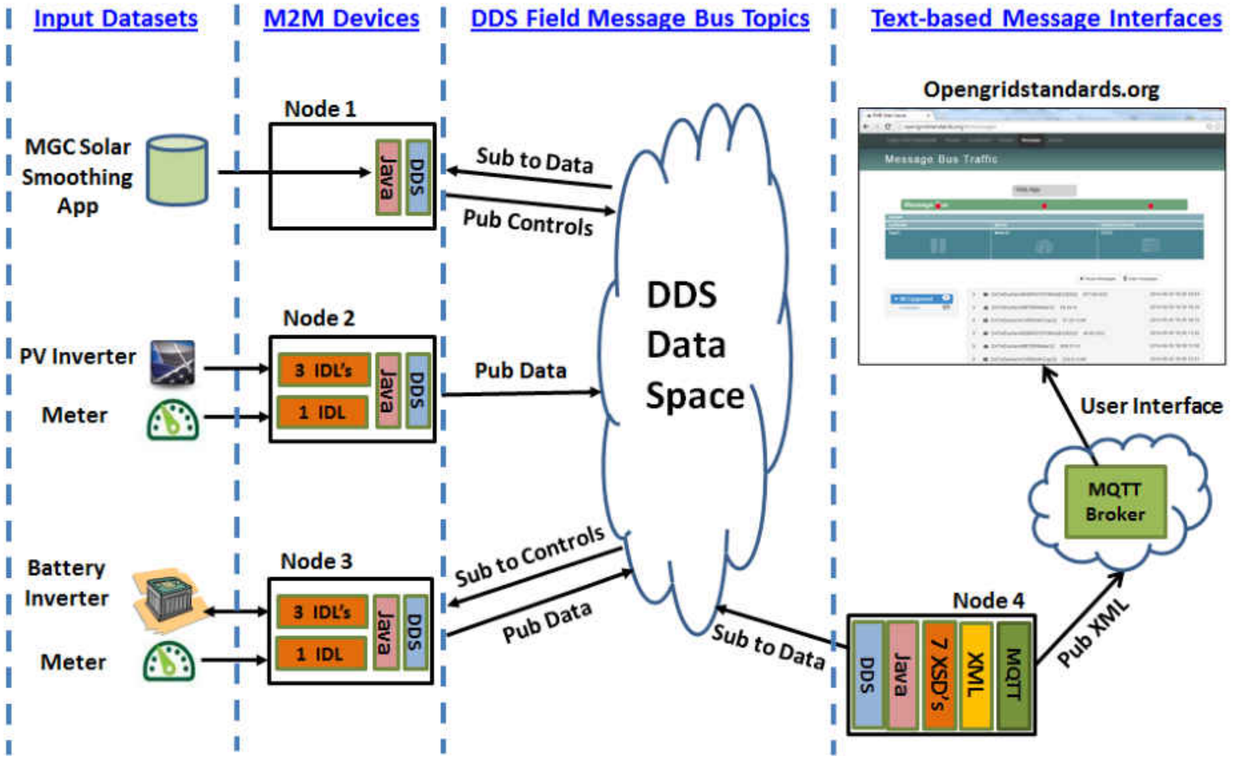
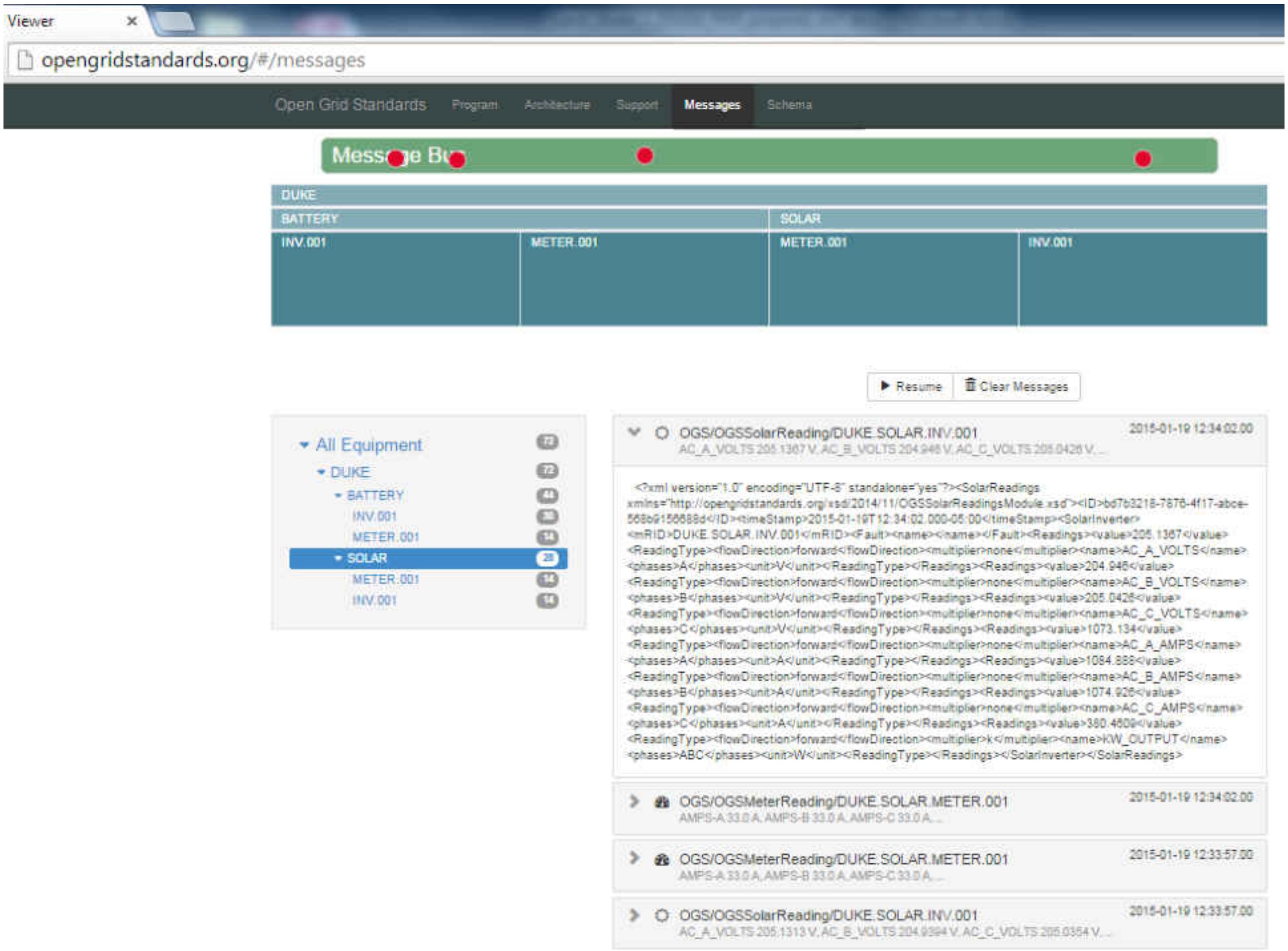


Figure 5-51: Configuration Setup for the FMB Demo using CIM/DDS and MQTT

5.5.2 Demo Results

Using a full day's worth of real grid data from one of Duke Energy's pilot test sites that had 1 MW of solar PV, a 500 kW of battery storage, and a solar smoothing app running live on Jan 19, 2015, the demo was implemented and repeated in a loop daily with a synchronized time-stamp. As exhibited in the screenshot below from the public website interface, in Figure 5-52, the publishing XML data topics from the MQTT broker client are streaming as planned and accurately validates the interoperability demonstration of the microgrid solar smoothing use-case topics in CIM.



OGS/OGSSolarReading/DUKE.SOLAR.INV.001 2015-01-19 12:34:02.00
AC_A_VOLTS 205.1367 V, AC_B_VOLTS 204.946 V, AC_C_VOLTS 205.0426 V, ...

```
<?xml version="1.0" encoding="UTF-8" standalone="yes"?><SolarReadings
xmlns="http://opengridstandards.org/xsd/2014/11/OGSSolarReadingsModule.xsd"><ID>bd7b3218-7876-4f17-abce-
568b9156888d</ID><timeStamp>2015-01-19T12:34:02.000-05:00</timeStamp><SolarInverter>
<mRID>DUKE.SOLAR.INV.001</mRID><Fault><name></name></Fault><Readings><value>205.1367</value>
<ReadingType><flowDirection>forward</flowDirection><multiplier>none</multiplier><name>AC_A_VOLTS</name>
<phases>A</phases><unit>V</unit></ReadingType></Readings><Readings><value>204.946</value>
<ReadingType><flowDirection>forward</flowDirection><multiplier>none</multiplier><name>AC_B_VOLTS</name>
<phases>B</phases><unit>V</unit></ReadingType></Readings><Readings><value>205.0426</value>
<ReadingType><flowDirection>forward</flowDirection><multiplier>none</multiplier><name>AC_C_VOLTS</name>
<phases>C</phases><unit>V</unit></ReadingType></Readings><Readings><value>1073.134</value>
<ReadingType><flowDirection>forward</flowDirection><multiplier>none</multiplier><name>AC_A_AMPS</name>
<phases>A</phases><unit>A</unit></ReadingType></Readings><Readings><value>1084.888</value>
<ReadingType><flowDirection>forward</flowDirection><multiplier>none</multiplier><name>AC_B_AMPS</name>
<phases>B</phases><unit>A</unit></ReadingType></Readings><Readings><value>1074.926</value>
<ReadingType><flowDirection>forward</flowDirection><multiplier>none</multiplier><name>AC_C_AMPS</name>
<phases>C</phases><unit>A</unit></ReadingType></Readings><Readings><value>380.4609</value>
<ReadingType><flowDirection>forward</flowDirection><multiplier>k</multiplier><name>KW_OUTPUT</name>
<phases>ABC</phases><unit>W</unit></ReadingType></Readings></SolarInverter></SolarReadings>
```

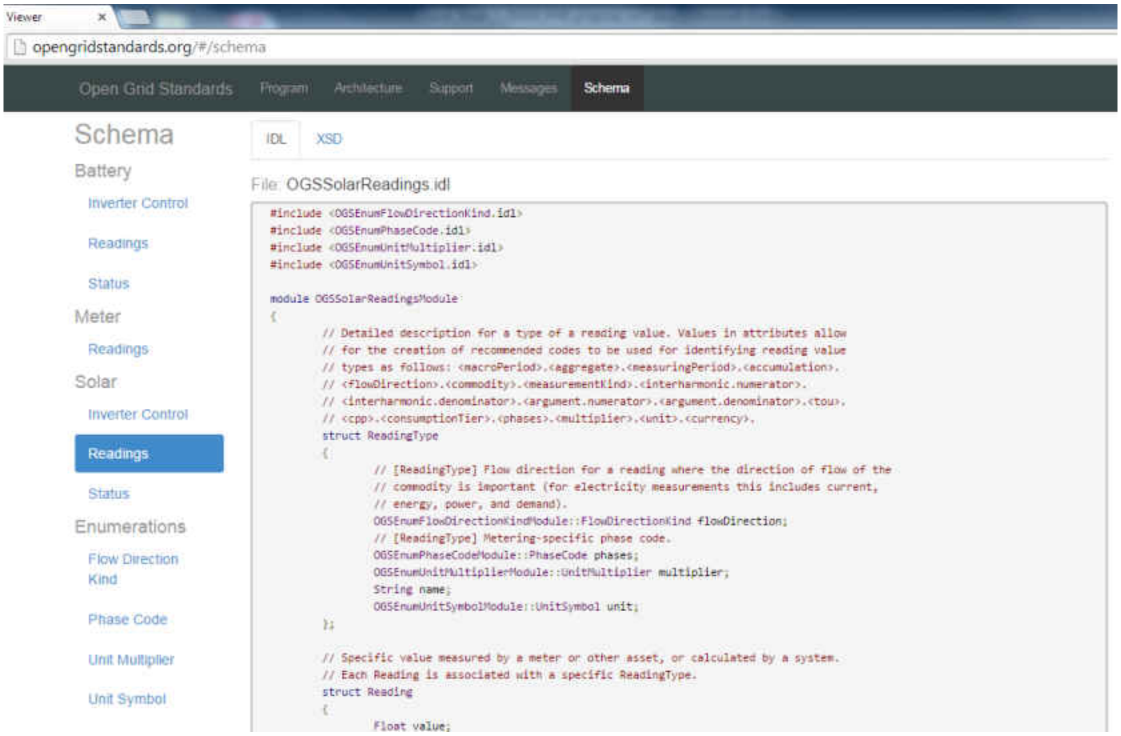
OGS/OGSMeterReading/DUKE.SOLAR.METER.001 2015-01-19 12:34:02.00
AMPS-A 33.0 A, AMPS-B 33.0 A, AMPS-C 33.0 A, ...

OGS/OGSMeterReading/DUKE.SOLAR.METER.001 2015-01-19 12:33:57.00
AMPS-A 33.0 A, AMPS-B 33.0 A, AMPS-C 33.0 A, ...

OGS/OGSSolarReading/DUKE.SOLAR.INV.001 2015-01-19 12:33:57.00
AC_A_VOLTS 205.1313 V, AC_B_VOLTS 204.9394 V, AC_C_VOLTS 205.0354 V, ...

Figure 5-52: Live Screenshot of the Microgrid Solar Smoothing Use-Case Demo

In addition to the live demo on the web interface to the MQTT cloud broker site, the opengridstandards.org website also contains all of the UML profiles associated IDL and XSD's in the case study. Figures 5-53 and 5-54, illustrate some example screenshots of the IDL and XSD files, respectively, for the SolarReadings module.



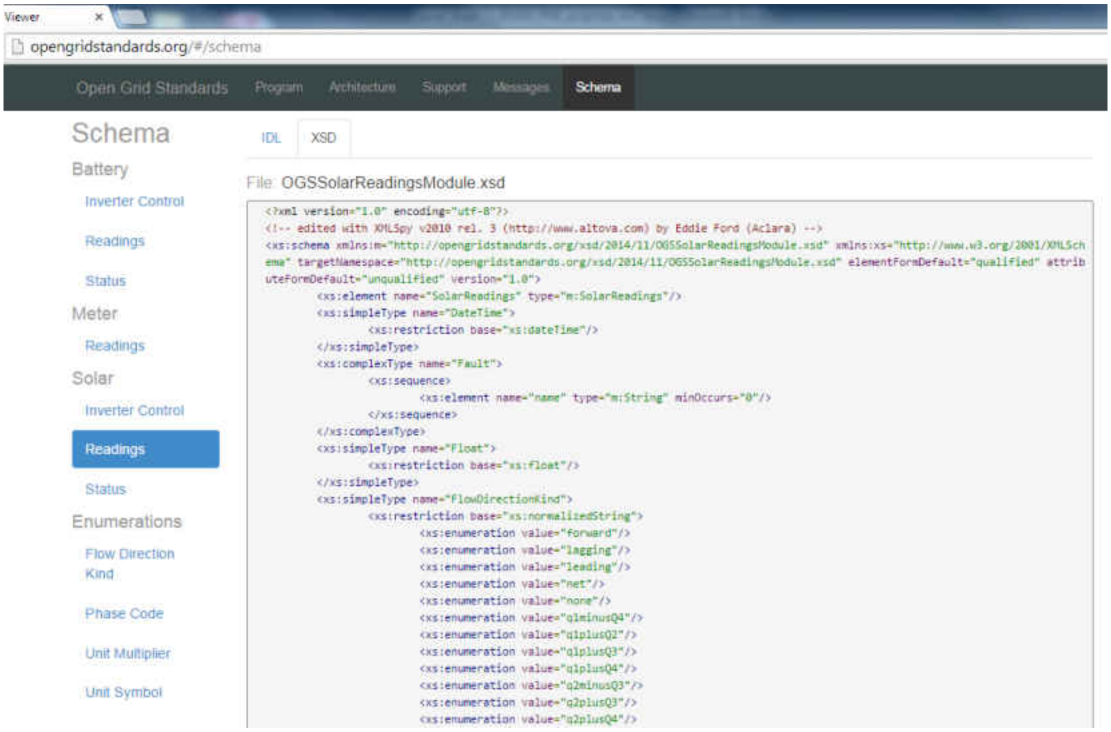
File: OGSSolarReadings.idl

```
#include <OGSEnumFlowDirectionKind.idl>
#include <OGSEnumPhaseCode.idl>
#include <OGSEnumUnitMultiplier.idl>
#include <OGSEnumUnitSymbol.idl>

module OGSSolarReadingsModule
{
        // Detailed description for a type of a reading value. Values in attributes allow
        // for the creation of recommended codes to be used for identifying reading value
        // types as follows: <macroPeriod>.<aggregate>.<measuringPeriod>.<accumulation>.
        // <flowDirection>.<commodity>.<measurementKind>.<interharmonic.numerator>.
        // <interharmonic.denominator>.<argument.numerator>.<argument.denominator>.<tou>.
        // <cpp>.<consumptionTier>.<phases>.<multiplier>.<unit>.<currency>.
        struct ReadingType
        {
                // [ReadingType] Flow direction for a reading where the direction of flow of the
                // commodity is important (for electricity measurements this includes current,
                // energy, power, and demand).
                OGSEnumFlowDirectionKindModule::FlowDirectionKind flowDirection;
                // [ReadingType] Metering-specific phase code.
                OGSEnumPhaseCodeModule::PhaseCode phases;
                OGSEnumUnitMultiplierModule::UnitMultiplier multiplier;
                String name;
                OGSEnumUnitSymbolModule::UnitSymbol unit;
        };

        // Specific value measured by a meter or other asset, or calculated by a system.
        // Each Reading is associated with a specific ReadingType.
        struct Reading
        {
                Float value;
```

Figure 5-53: Example Screenshot of the SolarReadings IDL Module



File: OGSSolarReadingsModule.xsd

```
<?xml version="1.0" encoding="utf-8"?>
<!-- edited with XMLSpy v2010 rel. 3 (http://www.altova.com) by Eddie Ford (Aclara) -->
<xs:schema xmlns:m="http://opengridstandards.org/xsd/2014/11/OGSSolarReadingsModule.xsd" xmlns:xs="http://www.w3.org/2001/XMLSch
ema" targetNamespace="http://opengridstandards.org/xsd/2014/11/OGSSolarReadingsModule.xsd" elementFormDefault="qualified" attrib
uteFormDefault="unqualified" version="1.0">
        <xs:element name="SolarReadings" type="m:SolarReadings"/>
        <xs:simpleType name="DateTime">
                <xs:restriction base="xs:dateTime"/>
        </xs:simpleType>
        <xs:complexType name="Fault">
                <xs:sequence>
                        <xs:element name="name" type="m:String" minOccurs="0"/>
                </xs:sequence>
        </xs:complexType>
        <xs:simpleType name="Float">
                <xs:restriction base="xs:float"/>
        </xs:simpleType>
        <xs:simpleType name="FlowDirectionKind">
                <xs:restriction base="xs:normalizedString">
                        <xs:enumeration value="forward"/>
                        <xs:enumeration value="lagging"/>
                        <xs:enumeration value="leading"/>
                        <xs:enumeration value="net"/>
                        <xs:enumeration value="none"/>
                        <xs:enumeration value="q1minusQ4"/>
                        <xs:enumeration value="q1plusQ2"/>
                        <xs:enumeration value="q1plusQ3"/>
                        <xs:enumeration value="q1plusQ4"/>
                        <xs:enumeration value="q2minusQ3"/>
                        <xs:enumeration value="q2plusQ3"/>
                        <xs:enumeration value="q2plusQ4"/>
```

Figure 5-54: Example Screenshot of the SolarReadings XSD Module

5.6 Summary

This chapter demonstrated the successful application of the interoperability framework in a form of a case study at a large investor owned utility (IOU) in the US. In order to effectively implement and verify the use-case application framework, a four step process was administered to define, model, map, and generate the common semantic syntax for 3 separate use-cases at Duke Energy. Upon completion of the process, a demonstration using real electric grid data, that was modeled in CIM and exchanged with DDS and MQTT pub/sub protocols, was performed and verified on a live streaming public cloud based website.

CHAPTER 6: VALIDATION AND FINDINGS

This chapter explains and delivers the final method for validating the proposed interoperability framework on the US electric grid infrastructure. The final validation instrument utilized for this research, in addition to the demo provided in the previous chapter during the case study, was a survey of a panel of experts across a number of different areas of technical specialization and a wide variety of disciplines or industries.

6.1 Survey Overview

In effort to validate this research, background materials on the interoperability framework, a live demonstration from the case study, and a survey were provided to a panel of 10 seasoned veterans in interoperability during a 1 hour web conference meeting. This group of panelists consisted of experts in a wide variety of skillsets, such Service-Oriented Architecture (SOA) integration, publish-subscribe (pub/sub) message-oriented middleware (MOM), and data modeling, across several different domain areas, such as utility, academia, consumer, industrial, defense, and the US government.

The selected panelists, whose biographies are located in Appendix A, are listed in table 6-1 below. Their experience ranged from 15 to 45 years, with an average of 28.7 years and standard deviation of 9.5 years. The survey administered consisted of 5 questions, with the first 4 of them focused on the validating the feasibility of the problem identified and methodologies utilized in the interoperability framework, whereas the last question was more open-ended and geared toward the future implications.

The detailed list of survey questions provided to the panelists were as follows:

1. Do you believe that the lack of interoperability is a concern for the US electric grid infrastructure, either today or in the future?
2. Do you believe that the proposed approach of translating (via pub/sub messaging) and contextualizing information (via CIM semantic models), outside the back-office data center, is a feasible method to enable interoperability between distributed grid assets and operational systems?
3. Do you feel that the use-case application framework is a feasible process for defining requirements and implementing interoperable topics for grid automation technologies to share and exchange on the field area network?
4. Do you feel that the proposed methodology of leveraging the combination of existing standards in utility data models (e.g. CIM), MBSE tools, (e.g. UML), schemas (IDL, XSD), and pub/sub middleware (e.g. DDS) is an effective framework for enabling interoperability for the US electric grid?
5. Can you think of any potential concerns that this interoperability framework might encounter during the development, implementation, and/or deployment processes at utility organizations?

Table 6-1: List of Selected Panelists Conducting the Survey

Panelist	Role	Industry	Expertise
Cory Casanave	CEO at Model Driven Solutions; Board of Directors at OMG	Defense	SOA integration; ontologies, data modeling; cybersecurity
Dominic Geraghty, Ph.D.	Executive Chairman, SEI; Managing Editor at smartgridix.com	Utility & Industrial	Utility executive; Interoperability panel
Erik Ljung	CTO at Room 5	Consumer & Industrial	Pub/sub middleware, Automated systems; IoT
Arlen Nipper	President/CTO at Cirrus Link	Industrial & Energy	Pub/sub middleware; Invented MQTT; SCADA systems
John Pastrana, Ph.D.	Research Associate at UCF	Academia & Industrial	MBSE tools; Interoperability simulation lab
R.W. Nick Stavros, Ph.D.	President/CEO at Jackrabbit Consulting	Defense	SOA integration; data modeling
Kostas Tolios	Principal Engineer at DTE Energy	Utility	Power systems; smart grid interoperability standards
Evan Wallace	Research Engineer at NIST	US Gov't	SOA integration standards; ontologies, data modeling
Frank Wilhoit	Principal at Broadheath Consulting; Retired Enterprise Architect at AEP	Utility	SOA integration standards; data modeling; IEC CIM TC57
Pamela Wise-Martinez	Sr. Strategic Enterprise Architect at Office of Director of Nat'l Intelligence; Former Chief Architect at DOE	US Gov't & Energy	SOA integration; data modeling; cybersecurity

6.2 Findings

The summary of results can be found below in Table 6-2. As exhibited, there was an unanimous consensus amongst the responses from the panel of experts. Though each answer confirmed the validity of the problem and the feasibility of the proposed solution and framework, the final question confirmed the potential concerns and challenges that this research concept will face as it is transferred into reality in the commercial or industrial setting and implemented in a highly regulated and change-resistant industry that has traditionally high barriers of entry for technology innovation. Moreover, though there was consensus on the end result of each question, it is worth summarizing a few sample quotes or comments per question to highlight the various insights and wide range of opinions that were included in the responses from the panel.

Table 6-2: Summary of Final Survey Results from the Panel of Experts

Question #	Casanave	Geraghty	Ljung	Nipper	Pastrana	Stavros	Tolios	Wallace	Wilhoit	Wise-Martinez
1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

In examining the final responses, available in Appendix B, the first question was intended to find out and confirm whether the lack of interoperability was a concern for the US electric grid, either today or in the future. In summary, all the panelists agreed and felt that it was indeed a problem today and needed urgent attention. Some of the potential concerns or issues mentioned in the panel responses were related to the barriers for energy efficiency, critical infrastructure security, affordability of upgrading the aging grid infrastructure, scalability, operational excellence, risk of failure of obsolete assets, flexibility of supply chain, and changing of organizational culture. Other challenges were related to the issues with the grid to embrace heterogeneity of components, the dynamic energy sources causing two-way power flow, and the future convergence of generation, transmission, and distribution of electricity. Furthermore, the lack of harmony of standards in the industry and the inability for utilities to quantify value or create revenue services in the smart home automation ecosystems has been a byproduct of the absence of grid interoperability.

In reviewing the second question, the purpose was to validate whether the proposed solution of translating data via publish-subscribe messaging middleware and contextualizing information via a common semantic model, such as CIM, is a feasible method for enabling interoperability between the grid assets and operational systems. In summary, all panelists again were in consensus that it was feasible and in many cases viable, but there were a wide range of opinions that were worth noting. One opinion mentioned that this proven, reliable, and secure paradigm avoids single points of failure or vulnerabilities that exist if all data routes through datacenter. Another opinion was focused on the improved visibility and situational awareness of the remote devices and the impracticality of the high latencies for the home automation, distributed generation, storage, and energy trading markets that required fast response times. Several surveys similarly described the maturity of applying IT technologies to OT technologies, along with common canonical data models, are already being standardized in other industrial IoT segments. Another expert brought up the potential "Big Data" issue that requires distributed intelligence to optimize and scale the traffic on the network before it reaching data center. Lastly, two panelists brought up the importance for not ignoring the protocol adapters needed to unlock the proprietary systems as the upper layers on the OSI stack.

In examining the third question, the objective was to validate the use-case application framework. Again, there was full agreement on the feasibility of the process and also was a wide range of insight provided. Many of the panelists felt the information modeling or "story-telling" process was an effective best practice in documenting requirements and defining boundaries. Others believe it was a key differentiator since it decoupled the various modeling and implementation layers, despite one comment that they wish there were more details on Platform Independent Models (PIMs). Moreover, others felt the syntax and middleware layers were mature frameworks, corresponding well to layers 4-7 of OSI model, and bolt well with the semantic layer. Lastly, one bold comment from a panelist was "this is not only a feasible process for determining correct requirements and implementing appropriate exchange forms providing interoperability, it is a preferred framework to meet actual requirements while avoiding unneeded extra implementation."

As for the fourth question, the goal was to validate whether the selections of existing standards were the appropriate combinations. As a final data point, the panelists once again confirmed the validity of this research by unanimously answering yes to the question. Given this question builds off of the previous two, there was less variation in the responses. Most of the feedback confirmed that the choice of standards was well-selected. Furthermore, a few panelists went even further to strongly mention that "it is the ONLY way" and "leveraging existing standards in this space is clearly the way to go in a space crowded with existing standards."

As described earlier in the previous section, the intent of the last question was not to validate the framework, but rather to provide an open-ended forum for the experts to contribute valuable insight and discuss some of the potential implications this framework could encounter if implemented in a real-world setting. Most of the feedback relates to the challenges that associated with the change management piece between organizations, vendors, and policy makers. For example, there were ideas for ensuring that utility organizations acknowledge that they have to change their way of managing and operating the grid, convincing major market vendor players with establish legacy infrastructure products view this overall interoperable ecosystem as a win-win scenario and that "interoperability does not necessary negatively impact their competitiveness," taking advantage of and documenting the power systems subject matter expertise before they leave workforce, and enforcing interoperability testing, compliance, certification, and device registration at utilities and standards organizations. Other feedback covered the deployment and implementation concerns, such as closely tying it to ROI to incentivize adoption and expose win-win situations, requiring an incremental approach for success, ensuring backward compatibility of the core OS and virtual components, encompassing requirements that can plug n play in different grid geographies, synchronizing the skill set requirements to operate the “complex network of things,” and mitigating of security threats that are not static and will continue to evolve. Lastly, from a modeling perspective, one panelist advised that the moving of the data models from the back-office data center to the field will create a “potential point of friction” since it could change the actor’s responsibility.

CHAPTER 7: CONCLUSION

This chapter provides a summary of the research activities documented in this thesis in order to develop, implement, and validate this dissertation's framework for enabling interoperability in the US electric grid infrastructure. Additionally, this chapter introduces and suggests some additional ideas or efforts that could enhance this framework or potentially make it a reality in the future.

7.1 Summary

As the US electric grid continues to undergo a transformation from a stable, one-way power delivery pipe to a stochastic, two-way power flow network, the need for interoperability will become more critical as the digital technologies being introduced to aging system are a heterogeneous mix of distributed generation (DG), electric vehicles (EVs), and smart home automation, that are all requiring much faster response times and very accurate situational awareness to ensure the safety, reliability, and security of the infrastructure. The nature of the recent smart grid infrastructure deployments has exacerbated the interoperability problem as it is mainly composed of single-purpose, siloed, expensive, and obsolete central systems that will require integration and co-existence with future technology solutions that are multi-function, modular, integrated, scalable, and future-proof system of systems (SoS). In order to enable the interoperability capability that can deliver fast response times and better local awareness, an approach that can unlock the existing tightly coupled proprietary interfaces via abstraction of the physical, logical, and network layers of the OSI model has been proposed outside of the data center integration operations.

However, in order to implement this new proposed solution to enable interoperability on the field area network (FAN) of the US electric grid, a thorough literature review on the topics of interoperability, message-oriented middleware, and common semantic models was required to narrow down the scope and identify the appropriate combination of mature and proven building blocks to seamlessly implement and simplify the complexity of integrating the IT technologies on the OT devices and systems. Moreover, even though the appropriate interoperability-enabling technology capabilities for translating (via pub/sub messaging middleware) and contextualizing (via common semantic data models) information outside the data center were understood, industrial engineering management tools were needed to investigate the organizational implications of change, develop a strategy map, and devise a balanced scorecard before a reference architecture was defined, implemented, and verified in its use-case application framework at a US electric utility. The case study that applied the interoperability framework at Duke Energy, which documented and demonstrated the process on how it can simply define and assemble each use-case in a standards-based and platform-independent approach, was verified via a prototype demo and validated via a survey to a panel of industry interoperability experts in the domains of power systems, SOA integration and middleware, and data modeling from the electric utility, consumer, industrial, defense, academic, and government sectors.

7.2 Framework

The primary outcome of this research is an use-case application framework that enables interoperability on the US electric grid by leveraging an open field message bus (FMB) reference architecture composed of modular and platform-independent building blocks that are based on mature industry standards for internet protocol (IP) networking, Internet of Things (IoT) communication protocols, international utility semantic models, and data modeling languages. As depicted in Figure 7-1 on the next page, this framework is a top-down process that is decoupled into 4 distinct layers, namely, the information modeling, semantic context, message syntax, and message-oriented middleware (MOM).

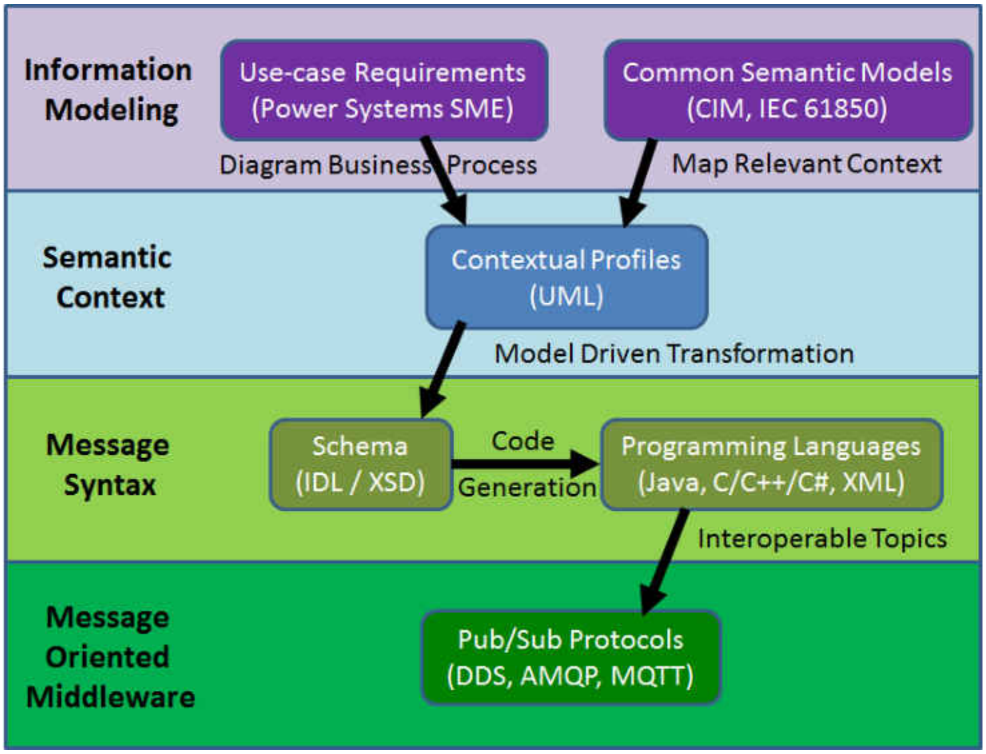


Figure 7-1: Use-case Application Framework for Interoperability on the US Electric Grid

7.3 Research Contribution

There were a number of research contributions to the body of knowledge that were exposed throughout this dissertation work. First, the research shed some light on the upcoming transformation that the electric grid is going through and the implications to the existing OT, IT, and telecom technologies deployed on the present infrastructure if the interoperability problem is not solved. Second, the introduction and cross-pollination of mature IT technologies from other industries, in order to unlock and abstract the local data that was previously siloed inside the proprietary OT devices, was revealed. Third, extensive literature review on the various definition and benefits of interoperability along with the study on message-oriented pub/sub middleware and utility data model standards was beneficial in effort to point out the apparent gaps that needed to be solved in the US utility industry. Fourth, the proposed solution of abstracting data outside the data center using standards-based IoT pub/sub middleware and common semantic models was a feasible interoperability approach for enabling a modular and scalable paradigm that can help utilities adapt more sustainability to the future dynamic grid ecosystem. Fifth, the availability and posting of the live steaming prototype demo on an open-source public website was envisioned to be an useful educational tool for fostering collaboration and sharing information among other stakeholders that can help them learn this framework quickly and enhance the level of participation needed to move this research concept to reality in the marketplace. Sixth, the publication of a reference architecture and its associated use-case application framework are important contributions to be used as a starting point for facilitating and expediting the development, implementation, and standardization of the proposed combination of use-cases, common data models, syntax structures, and middleware protocols in the US utility industry. Seventh, the development process of leveraging industrial engineering management tools, such as the matrix of change (MOC), strategy maps, and a balanced scorecard was unique for this industry and could be used as a powerful tool for communicating future grid strategy roadmaps to non-technical stakeholders. Last, but not least, the use of the industrial engineering best practices in system engineering was a critical instrument and valuable catalyst necessary for taming the complexity of integrating the major disparate electric grid components, such as hardware equipment, telecommunications, and IT software, which have traditionally created functional siloes within the utility organizations associated with the various disconnected and specialized engineering disciplines, such as mechanical engineering, electrical engineering, and computer science, respectively.

7.4 Future Work

As the last question of the survey in Chapter 6 was intended to point out potential concerns with the framework as it moves from research concept to practice, there was a lot of valuable feedback provided by the panelists to be considered for future work. Starting with the concerns over established vendors not changing their business model to accommodate this framework, there will need to be industry-wide efforts to convince these major players that unlocking data locally to deliver interoperability with other vendors systems outside their data center head-end server will not negatively impact their product's competitiveness, security, or reliability.

Addressing concerns about the enforcement of interoperability standards, there will need to be industry standardization bodies that can influence the stakeholders within the utilities procurement organizations to incorporate requirements into their supplier contracts. These requirements, which need to be developed and ratified by a national or international standards body, will have to include details and procedures for testing, compliance, and certification of this interoperability framework. From a standardization development process, a non-profit or third-party repository will need to be created, maintained, and available to the industry like the IEC TC57 CIM data models are in the UCAIug. Likewise, there will need to be a common portal or "Apps store" for the utility for the access to the legacy protocol adapters, middleware, and data model profiles for the SME-defined grid use-cases. Last, but not least, there will need to be a significant investment in cybersecurity capabilities and mitigated security threat scenarios before for distributed applications with middleware and data models can be deployed outside the firewall of the utility central office enterprise datacenter.

APPENDIX A: BIOGRAPHIES OF PANEL OF EXPERTS

BIOGRAPHY OF CORY CASANAVE

Cory Casanave is a recognized expert and thought leader for actionable agile architectures at all levels; making enterprise, business, process, information and services architectures meet business needs while directly supporting executable I.T. solutions using Model Driven Architecture (MDA). With over 30 years of experience in standards, product development and solving mission problems, Mr. Casanave provides a unique perspective on solving enterprise, government and industry problems with business focused technology solution. Mr. Casanave's current focus is broad-based information sharing and federation and is the chief architect of the community initiative and standards effort to address the sharing and analytics of cross-domain threat and risk information sharing, a crucial capability for government and industry.

Mr. Casanave is a member of the Object Management Group (OMG) board of directors and co-chairs the OMG's Government task force. OMG activities include authoring the white paper "Transforming Government I.T. With Architecture – achieving agility and modularity" which defines an architectural approach to achieving the administration's 25 point plan. Additional OMG activities include the SoaML, BPMN, UML, NIEM, Semantic Web and Information Federation standards.

In support of Government/Industry collaboration Mr. Casanave helped the U.S. National Information Exchange Model (NIEM) program office create the new standard for model driven information exchange data – NIEM-UML. In support of information sharing and enterprise integration Mr. Casanave was also one of the authors of "SoaML" – the modeling standard for SOA.

Mr. Casanave was the principle investigator on several DHS research grants for improving application assurance through application of model driven evaluation of software systems.

In his commercial role Mr. Casanave is CEO of Model Driven Solutions (www.modeldriven.com), a services organization specializing in architected solutions for government and enterprise clients. ModelDriven.org, the open source arm of MDS, hosts open source projects for Model Driven Architecture - ModelPro, SOA, Linked Open Data and Executable UML.

BIOGRAPHY OF DOMINIC GERAGHTY, PH.D.

Dr. Dominic Geraghty is Executive Chairman, Smart Energy Instruments (SEI), He is a senior consultant to the Smart Grid Interoperability Panel (SGIP). He is also Founder/Managing Editor of www.smartgridix.com, a dialog- and services-based website focused on developing business cases for Smart Grid applications. He is an Executive-in-Residence at EnerTech Capital Partners. He brings over 30 years of industry experience.

He was senior equity investment consultant at Oaktree Capital/GFI Ventures in 2010-2011. Before that, he was Executive Chairman of the Board of Tantalus Systems Corporation, an AMI/Smart Grid company; from 2007 – 2009, he was CEO of Tantalus. Prior to that, he served as Executive Chairman of the Board of The NanoSteel Company, Inc. As Senior Vice-President of M&A, Catalytic Energy Systems, Inc. (NASDAQ: CESI), he acquired SCR-Tech LLC , an early-stage NOx-catalyst regeneration company, which was sold in 2011 for $101 million. Before that, he co-founded and was co-CEO of Enerwise Technologies, which was acquired by Comverge (NASDAQ: COMV) for about $75 million. He was President of Genesis Services, a division of Itron (NASDAQ: ITRI); founder/President of Energy Technologies Inc. (an unregulated subsidiary of Atlantic Energy -- a $250 million venture fund focused on energy-related investments); general partner at Arete Ventures, focusing on investments in energy-related companies; Director, R&D Programs at the Electric Power Research Institute.

Mr. Geraghty received B.E. and Ph.D. degrees in Chemical Engineering from University College, Dublin, Ireland, and an M.B.A. degree from University of Santa Clara, California.

BIOGRAPHY OF ERIK LJUNG

Erik Ljung is the chief technology officer at Room 5. In his role, Erik, a 15-year software veteran, is responsible for developing the company's long-term technology and consulting vision in the emerging IoT (Internet of Things) space.

Prior to transitioning to the CTO role, Erik served as Head of Delivery for Room 5's professional services where he lead the transition from embedded and mobile software development into high-end software consulting niched at user experience focused end-to-end software solutions. Erik has an extensive background leading and driving all phases of embedded, cloud and mobile software projects. He personally managed an early IoT project for DARPA that focused on connectivity and interoperability between a proprietary sensor mesh technology and modern mobile systems.

Erik holds a M.Sc. in Computer Science from the Faculty of Engineering, Lund University in Sweden.

BIOGRAPHY OF ARLEN NIPPER

Key Highlights

- 36 years of direct experience in the embedded computer industry
- 10 years of Oil/Gas SCADA systems engineering with Amoco and Koch Oil
- Cofounder of NovaTech as VP of Engineering
- President of Arcom Control Systems
- Developed AT&T's VSAT SCADA infrastructure protocol (SNET)
- Co-developed MQTT with Andy Stanford Clark (IBM)
- Board member of the HART Communications Foundation (6 years)
- President and CTO of Eurotech Inc.
- Executive presentations for IBM, Intel, Stanford University CTO Forum
- Helped establish the Eclipse Foundation M2M Industry Work Group
- Helped get the OASIS MQTT Standards Group established.

Arlen Nipper has been designing embedded computer hardware, software and solutions for 36 years. Arlen graduated from Oklahoma State University and worked in the oil patch for 10 years learning tons of useful stuff about "how things work" in the real world. The next part of Arlen's career path led to signing up with a startup technology company called NovaTech providing design and integration services using embedded computer technology. NovaTech was a successful startup and became Arcom Control System and then Eurotech Inc. over the last 20 years. Arlen was the President and CTO of these OEM computer-manufacturing and software solutions companies.

Arlen is now the co-founder and President/CTO of Cirrus Link Solutions. Across his entire career Arlen has been passionate about applying embedded computer technology to existing paradigm problems in the industrial controls and automation market sector. But in recent years he has stepped back from just the hardware/software aspects of embedded systems and started to view the entire ecosystem of hardware, software, security, infrastructure, IT, and ultimately the people being served by the this hugely interesting, emerging "Internet of Things."

BIOGRAPHY OF JOHN PASTRANA, PH.D.

Dr. John Pastrana is a Research Associate at the University of Central Florida (UCF) Simulation Interoperability Laboratory. He brings over 15 years of experience in project management and development of complex engineering systems design efforts. He also has experience in sales engineering and new business development services.

Dr. Pastrana's current role is as academic researcher and consultant in the areas of distributed and hybrid simulation systems with parallel computing capabilities, such as synthetic simulation environments, 3D graphical assets, and terrain map/feature developments for the implementation of training systems and training effectiveness measurement techniques. He also brings engineering management skills to encompass the areas of operational management, quality management and improvement, new business process modeling, engineering economic analysis, discrete/continues simulation, agent-based modeling and decision analysis methodologies.

Dr. Pastrana has a bachelor's degree in Electrical Engineering from UCF and master's and doctorate degrees in Industrial Engineering from UCF.

BIOGRAPHY OF R.W. NICK STAVROS, PH.D.

R. W. Stavros, Ph.D. has been in the computer industry for almost 45 years and has extensive experience in many aspects of computing including Operating Systems, embedded applications, and large scale application that require almost a hundred engineers. Many of the application have long life spans covering decades. for the last 12 years he has focused on net-centric and interoperability issues while supporting the US Navy, PEO C4I as the Technical Lead for the Net-Centric Enterprise Solutions for Interoperability (NESI) http://nesipublic.spawar.navy.mil.

Dr. Stavros is president of Jackrabbit Consulting, LLC, being an active member of the Object Management Group (OMG), Chair of the Cloud Computing Working Group, and co-chair of the Ontology Working Group. He has been an active in the OMG Middleware and Related Devices (Mars) vices Platform Task Group (PTF) and a key contributor to the Data-Distribution Services (DDS) Special Interest Group (SIG). He has worked on most of the DDS specifications including the DDS Security Specification which is under finalization.

Dr. Stavros has completed his bachelor's degree in Botany and Plant Pathology from Colorado State University and his masters and doctoral degrees in Environmental Sciences and Engineering from the Virginia Polytechnic Institute and State University.

BIOGRAPHY OF KOSTAS TOLIOS

Kostas Tolios is a Principal Engineer, Power Systems Technologies at DTE Energy's (formerly Detroit Edison) Engineering Research Department.

Throughout his 34 year career, he has held several Engineering positions and has worked in projects related to High Voltage AC/DC testing, Energy Conversion, Electric Vehicles, Power Quality, Harmonic Energy Propagation and effects of non-linear loads, Cogeneration, Transformers, Motors, Generators and Auxiliaries both in Fossil and Nuclear Power Plants, AMI/MDMA/DR/DSM testing and implementations and Electric Choice (Retail/Wholesale) implementation. He has extensive experience in testing and evaluating advanced automated metering networks (Electric/Gas/Water) and smart grid technologies that resulted in establishing the DTE Energy's Advanced Metering Engineering and Metrology Laboratory. He is currently working in the Power Technologies group developing and evaluating smart grid technologies, renewable energy and interoperable standards. He is contributing member of several ANSI C12 .XX/ IEEE 170X and UCA/IEC working group committees.

Kostas holds a BS in Electrical Engineering from Manhattan College, NY and a MS in Power Systems Engineering from Ohio State University, OH. He also has a MS in Mechanical Engineering from Wayne State University, MI.

BIOGRAPHY OF EVAN WALLACE

Evan Wallace is an electronic engineer in the Systems Engineering Group under the Systems Integration Division (SID) of the Engineering Laboratory (EL) at the National Institute of Standards and Technology (NIST). He joined NIST in 1984 originally working on communication systems in the Automated Manufacturing Research Facility (AMRF). He has spent 30 years at NIST working on integration of systems and data in industrial environments. His current responsibilities include investigating architectures, standards, and practices to enable smart manufacturing. His focus has been on models, languages, technologies and standards for system integration for manufacturing and other technical domains with a concentration on ontologies and conceptual modeling.

He was a member of the NIST Smart Grid Framework and Roadmap team, a contributor to the NAESB Energy Usage Information Model, and a key member of the standards group developing the ASHRAE Facility Smart Grid Information Model (FSGIM). He was a co-editor of the latest Web Ontology Language (OWL) recommendation and represented NIST in other Semantic Web standards groups. He is a co-chair of the Ontology Special Interest Group at OMG and championed the development of the Ontology Definition Meta-model (ODM) specification and the Data Acquisition for Industrial Systems (DAIS) specification at OMG. He was also a member of the SP-95 working group at ISA that developed part 1 of the ISA-95 standard for Enterprise – Control System Integration. He was also a member of the SGIP Industry to Grid Domain Expert Working Group (DEWG) and multiple Priority Action Plans (PAPs).

He was a graduate from George Mason University with a Bachelor of Science in Computer and Electronic Engineering..

BIOGRAPHY OF FRANK WILHOIT

Frank Wilhoit has 32 years' experience in all aspects of software development and is presently working as a consulting information architect in with the electric utility industry. He is a member of Technical Committee 57 of the IEC, the body charged with developing the standards collectively known as the Common Information Model.

As Enterprise Information Architect for American Electric Power (AEP) from 2003 -- 2014, Frank led the implementation of CIM-based integrated solutions for metering (retail and commercial/industrial), energy efficiency/demand response, and outage management.

BIOGRAPHY OF PAMELA J. WISE-MARTINEZ

Ms. Wise-Martinez is a strategic technology and business leader with over 20 years of experience in innovation, research and development, architecture and systems engineering. As a futurist, she is driven to create a business evolution through service architecture and innovation. Today, Ms. Wise-Martinez is Senior Strategic Enterprise Architect for the Office of the Director of Intelligence (ODNI), responsible articulating and delivering the Information Sharing Environment (ISE), Interoperability Framework Integrated Landscape (I2FIL). The I2FILimplements a holistic approach using cross-linking business and technical management disciplines in Architecture, Profiles, and Industry Standards and Specifications.

As the Chief Architect at the National Nuclear Security Administration, Department of Energy, she architected the Cloud Service Layer Architecture, articulating an Enterprise Lifecycle Management approach, Conceptual Architecture, Prescriptive Architecture and Transition Plan, implementing enterprise governance approach via FEA, TOGAF and SOA, and the best business practices Cloud Computing, IPv6, Shared Services and Identity and Credential Access Management strategies, recognized as a Center of Excellence in EA Governance. As the Principal Organizational Change Project Lead, for the largest Enterprise Resource Planning (ERP) system deployment in the federal government, the “Financial Business Management System (FBMS)” over 800 million dollars, at the Department of Interior. She led the analysis of over 200 reengineered business processes, through enterprise communications, delivering business- to-technology strategic alignment, developing key performance metrics, providing executive coaching, and business impact and risk assessments for key business owners and training to over 65,000 end-users, via ACENDENT methodology.

As the Chief Technology Officer, and Application Integration Architect for the U.S. Department of Homeland Security (DHS) Cyber Crimes Center, she drove first adoption of VoIP, SOA, XML, XHTML, BPEL, BPMN and secure object oriented solutions and encrypted data base transactions, supporting computer forensics, Internet crime, and child exploitation. Pamela has designed, delivered and integrated multiple high-profiled international systems for public and private industry while forming collaborative partnerships with Academia, high-tech private industry, integrators, and numerous government and not-for-profit organizations.

Ms. Martinez has a Masters of Science in Engineering and Technology Management from George Washington University and Certified in Governance of Enterprise IT from ISACA.

APPENDIX B: SURVEY RESPONSES OF PANEL OF EXPERTS

SURVEY RESPONSES OF CORY CASANAVE

1. Do you believe that the lack of interoperability is a concern for the US electric grid infrastructure, either today or in the future?

Answer: ***While I am not a "grid professional", my understanding of the issues from this presentation, friends that have worked smart grid, various government programs and general media indicate to me that lack of interoperability is a substantial barrier to energy efficiency and the security of critical infrastructure. So, yes.***

2. Do you believe that the proposed approach of translating (via pub/sub messaging) and contextualizing information (via CIM semantic models), outside the back-office data center, is a feasible method to enable interoperability between distributed grid assets and operational systems?

Answer: ***Absolutely. Distributed pub/sub is a proven and reliable system of systems pattern. It makes sense that "moving it out of the data center" would avoid single point of failure (and vulnerability) as well as substantially improve reaction time of connected systems. A reliable and secure infrastructure like DDS is critical.***

3. Do you feel that the use-case application framework is a feasible process for defining requirements and implementing interoperable topics for grid automation technologies to share and exchange on the field area network?

Answer: ***The use case, requirements, sequence diagram and data model framework looks very solid as well as easy to comprehend. Using a model based approach makes a lot of sense to join requirements with solutions and make sure the environment is agile as components, protocols and data change (and they will). I would add that specific stories and examples, with real data, is also critical for validating such a design. This was also demonstrated in the presentation.***

4. Do you feel that the proposed methodology of leveraging the combination of existing standards in utility data models (e.g. CIM), MBSE tools, (e.g. UML), schemas (IDL, XSD), and pub/sub middleware (e.g. DDS) is an effective framework for enabling interoperability for the US electric grid?

Answer: The choice of standards seems well chosen and they work together effectively. I would expect that as the approach grows reference standards other than CIM may need to be integrated, but that should be viable within the

approach. I am happy to see Units handled, consider some of the standards for units from NIST.

5. Can you think of any potential concerns that this interoperability framework might encounter during the development, implementation, and/or deployment processes at utility organizations?

Answer: As always, the assurance and security concerns are critical, but outside of the specific research. One thing that can be considered with a model based approach is hardening of the provisioning pattern and supporting infrastructure – such that once that is thoroughly validated and hardened the resulting protocols and implementations can be more trusted (of course they need to be validated as well). Consider capabilities (Such as OMG KDM Standards) which allow multiple static and dynamic system assurance tools to be integrated for better resolution of vulnerabilities.

To allow for greater agility, reuse and future-proofing, consider a bit more abstraction in the data model. It would seem concepts like events, status and units could be more abstracted and reusable without introducing runtime overhead.

Of course while the translation nodes are necessary for legacy systems, the same capability could be embedded in future products that are data model and protocol aware.

None of the above should detract from the work, these are aspects that can expand on the approach as presented.

SURVEY RESPONSES OF DOMINIC GERAGHTY, PH.D.

1. Do you believe that the lack of interoperability is a concern for the US electric grid infrastructure, either today or in the future?

Answer: It is a major concern. The industry is transitioning to a Smart Grid -- the ultimate Smart Grid, by definition, is an interoperable, interconnected, grid that provides for control, automation, and optimization of grid operations. However, electric utilities are not going to replace long-lived useful assets using legacy/proprietary systems to achieve interoperability - it is too expensive. Therefore, control, automation, and optimization systems have to able to include these legacy systems using a combination of APIs and mature standards. Furthermore, the business case for most Smart Grid applications consists of a "stack" of benefits, some of which would not accrue without interoperability.

2. Do you believe that the proposed approach of translating (via pub/sub messaging) and contextualizing information (via CIM semantic models), outside the back-office data center, is a feasible method to enable interoperability between distributed grid assets and operational systems?

Answer: As end-users of electricity increasingly use smart energy appliances, distributed generation and storage, and automatic price response algorithms, utilities need to have visibility into what the end-users are doing in order to properly dispatch supply to meet net demand and to ensure the reliability, stability and security of the grid. There will not be enough time to send information to centralized enterprise systems, make a decision, and then back to edge for some critical Smart Grid applications. The proposed approach here overcomes this challenge.

3. Do you feel that the use-case application framework is a feasible process for defining requirements and implementing interoperable topics for grid automation technologies to share and exchange on the field area network?

Answer: Yes - in my view the first step in designing and implementing a grid automation is to develop a requirements document for a use case. The best people to define the requirements are the users of the solution. The requirements document is also a prerequisite in the procurement process. I would also add that the use case is necessary but not sufficient per se -- a business case, based on combining the results of the use case and other cost and market factors, is required to justify an investment in the grid automation product.

4. Do you feel that the proposed methodology of leveraging the combination of existing standards in utility data models (e.g. CIM), MBSE tools, (e.g. UML), schemas (IDL, XSD), and pub/sub middleware (e.g. DDS) is an effective framework for enabling interoperability for the US electric grid?

Answer: Conceptually, this approach makes sense. Use as much of what is already available. Identify the "gaps" related to interoperability, and bridge these gaps with APIs/translators. The approach proposed here appears very efficient in terms of providing an ability to collect and operate on only the information that is necessary for the application in question. And it meets the essential requirement of maintaining the parallel centralized communication and control system with which the utility is familiar and which can meet some of the requirements of utility operations for some time to come.

5. Can you think of any potential concerns that this interoperability framework might encounter during the development, implementation, and/or deployment processes at utility organizations?

Answer: The two biggest challenges in implementing the framework is (a) changing the way the organization thinks and works from the traditional way of operating the grid to the new Smart Grid approach - it is a change in "the way of life" of the utility, and (2) convincing the vendors that interoperability does not necessarily negatively impact their competitiveness

SURVEY RESPONSES OF ERIK LJUNG

1. Do you believe that the lack of interoperability is a concern for the US electric grid infrastructure, either today or in the future?

Answer: Yes, Comparing for instance with the smart home automation, interoperability is the necessary vehicle to drive an upgradeable and scalable infrastructure.

> ***• Combinations of vendor specific solutions enable new use---cases by leveraging distinct functionalities without enforcing ongoing large infrastructure investments. The cost for those use-cases without interoperability would potential not deliver expected ROI. A smart connect refrigerator would enable low ROI use-cases, but when it is interconnected with other items it would potential expose high ROI use-cases.***
>
> ***• A non-interoperable architecture is sensitive to vendor stability and product life-cycles which usually implies large costs for maintenance and/or upgrades. Interoperability acts as a multiplier for service---based industries, where systems are built up from various vendor specific components. The end-users or the primary use-cases is what drivers the overall revenue of such a system.***

In summary; an interoperable framework is a valid approach to enable new technology and vendors in the domain, improve end-user services, revenue driving primary use---cases and optimizing any costs related to maintain the grid.

2. Do you believe that the proposed approach of translating (via pub/sub messaging) and contextualizing information (via CIM semantic models), outside the back-office data center, is a feasible method to enable interoperability between distributed grid assets and operational systems?

Answer: Yes. The recent IoT reference model published by Cisco and IoT World Forum (http://cdn.iotwf.com/resources/72/IoT_Reference_Model_04_June_2014.pdf) proposes the approach to decouple information technology and operational technology. In comparison with the current "back-office" solution the distributed node concept would enable:

• "Edge Computing" – fast, local, seamless decision making on operational data

• Reduce data size and latency for informational data

• System scalability

- ***A more resilient infrastructure***
- ***Architectural agility – ease on-ramp of new "nodes"***

3. Do you feel that the use-case application framework is a feasible process for defining requirements and implementing interoperable topics for grid automation technologies to share and exchange on the field area network?

Answer: ***Yes, A key differentiator for the use-case application framework is to be decoupled from any implementation specifics. For a use-cased based strategy to be efficient the implementation options needs to be left open for interpretation, granted it stays inside the boundaries of what the framework and the model propose.***

4. Do you feel that the proposed methodology of leveraging the combination of existing standards in utility data models (e.g. CIM), MBSE tools, (e.g. UML), schemas (IDL, XSD), and pub/sub middleware (e.g. DDS) is an effective framework for enabling interoperability for the US electric grid?

Answer: Yes, It is important to realize that the emerging IoT technologies that enable the development of the proposed distributed node hierarchy would be impacted by the various limitations of these technologies; cost, power management, connectivity, compute power (e.g. for security) and tools.

The concept of "edge computing" is rapidly emerging new sets of communication protocols, tools, ultra---low power devices and security paradigms in other verticals. The methodology should be flexible enough to account for future potentially disruptive technologies that are getting traction.

5. Can you think of any potential concerns that this interoperability framework might encounter during the development, implementation, and/or deployment processes at utility organizations?

Answer: Yes

Deployment – as with any interoperability framework the incentive for adoption needs to be closely tied to a ROI or expose win---win situations. Similar to smart home automation framework, the nature of a service---based model enables vendors to be incentivized to adopt without forcing a disruptive change in their own model. Large existing systems are already deployed and "paid for".

The uPnP AV standard is an great adoption due to “certification” of products that lead to up---swing in product marketing and a clear ROI for the vendors but the various implementations and interpretations of the standard did not achieve the intended result in interoperability. uPnP also suffered tremendously from the early absence of a built---in security architecture, which is obviously a necessity for the grid infrastructure.

Implementation– There needs be enough room for interpretation in the framework to incentivize innovation and competition. Obviously, to the point made about uPnP, it needs to be carefully governed by the framework itself; else the outcome would defeat the purpose of the actual framework. It’s a fine balance that needs to be tuned over time, but as critical to point out.

In summary; I believe the high-level proposed approach to address the problem statement is solid and anchored in the latest thoughts in IoT, distributed connectivity and security. The general theme of my feedback is the clarity of decoupling of implementation vs. architecture and model

SURVEY RESPONSES OF ARLEN NIPPER

1. Do you believe that the lack of interoperability is a concern for the US electric grid infrastructure, either today or in the future?

Answer: Yes. I believe that the lack of interoperability between devices and "Applications" written to connect to these devices (IED's for the Electric SCADA space) is on of the greatest challenges that face customers today and going into the future. The tight coupling of bespoke protocols to bespoke applications limits the ability to embrace new device technology in the field and severely impacts the "serendipitous" use of device data on any application other than SCADA host on the corporate backend. Moving at the "Speed of Technology" will help operators deal with both security and operational excellence both today and moving into the future. But in order to accomplish this the legacy notion of tightly coupled device to application model MUST be replaced by decoupling intelligent field device from any single application.

2. Do you believe that the proposed approach of translating (via pub/sub messaging) and contextualizing information (via CIM semantic models), outside the back-office data center, is a feasible method to enable interoperability between distributed grid assets and operational systems?

Answer: Yes. Applying mature "IT Technologies" where appropriate to "OT infrastructures" pulls mainstream technology, security practices, and resources (developers, applications, services, etc.) into legacy electric grid infrastructures. Pub/Sub technologies provide the required decoupling between the devices and applications while contextualizing the resulting process variable information frees up the information for general consumption by other "Line of Business" applications. Currently, Electric Grid SCADA host systems on the only consumer of data and from that standpoint are required to parse/understand data flowing in proprietary protocols. By decoupling, describing, and publishing this data (securely and with proper ACL) the SCADA Host can still remain an IMPORTANT data consumer, but not the ONLY data consumer.

3. Do you feel that the use-case application framework is a feasible process for defining requirements and implementing interoperable topics for grid automation technologies to share and exchange on the field area network?

Answer: Definitely! MQTT and DDS are both mature Pub/Sub messaging technologies that have been around for at least a decade and used mission

critical operational infrastructures as will had high speed and reliable IT applications. The notion of "Edge of Network" devices providing protocol conversation, TCP/IP connectivity, and security is a well-established product sector as well. With the underlying framework in place, working towards an interoperable "Topic Namespace" becomes not only feasible, but very demonstrable.

4. Do you feel that the proposed methodology of leveraging the combination of existing standards in utility data models (e.g. CIM), MBSE tools, (e.g. UML), schemas (IDL, XSD), and pub/sub middleware (e.g. DDS) is an effective framework for enabling interoperability for the US electric grid?

Answer: Yes. In my opinion it is the ONLY way. 35 years ago SCADA systems required half duplex, poll/response protocols in order to work over the communications circuits that were in use at the time.

But this is 2015 and TCP/IP has all but replaced any notion of a multi-drop telecom communications circuit. Therefore poll/response protocols will disappear as intelligent devices and Edge of Network interfaces are able to determine what process variable data to send and when to send it. As poll/response protocols disappear so will the proprietary nature of register/packet based data representation used within these protocols. Self-defining schema technologies already leveraged by IT will be used to deliver data to multiple data consumers in a manner that each can consume it appropriately. This has already been implemented and deployed in Oil/Gas SCADA systems for over a decade now and I believe it's time for the entire technology suite to be applied to the Electric Grid infrastructure as well.

5. Can you think of any potential concerns that this interoperability framework might encounter during the development, implementation, and/or deployment processes at utility organizations?

Answer: At the first level, major players that are already established in the market will see this approach as a treat to existing legacy infrastructure and devices. So care must be taken to ensure that the overall eco-system of device manufactures, application providers, and services providers see this a win-win scenario. With that being said within the larger M2M/IIoT (Industrial Internet of Things) it is already happening and it is inevitable these technologies will move into the Operations space. Doing it now with a well-established set of SME's and

industrial customers will not only make it happen sooner, but with much better results and interoperability.

Also I think that it's important to note that in addition to XML technologies for the message transport of process variable information, JSON technologies are quickly becoming the primary data representation format used by IT and associated Web Applications. Especially in light of the fact that now application developers could gain secure access directly into Middleware using the new WebSockets technology. Think of what could be accomplished with small, lightweight, run anywhere on anything type Web Applications that could tap directly into the Middleware Message stream!

SURVEY RESPONSES OF JOHN PASTRANA, PH.D.

1. Do you believe that the lack of interoperability is a concern for the US electric grid infrastructure, either today or in the future?

Answer: Yes. Successful implementations of new technologies that support the US electric grid infrastructure depend on proper enterprise interoperability as "smart" components or devices get introduced into the system. Organizational and operational aspects inherent to the production and delivery of electricity/power into the grid will benefit with the increase levels of data connectivity and secure access to critical system information. In addition, higher level of efficiency and effectiveness of O&M personnel day to day activities can be expected as easily accessible/usable data can be shared among the different stakeholders in the system to increase collaboration.

2. Do you believe that the proposed approach of translating (via pub/sub messaging) and contextualizing information (via CIM semantic models), outside the back-office data center, is a feasible method to enable interoperability between distributed grid assets and operational systems?

Answer: Yes. The technical approach defined in the proposed framework will support the necessary data interconnectivity and collaboration at all levels along the supply and demand operations in the US electric grid infrastructure. The use of OMG standards and the contextualization method presented will provide the necessary guideless to support the increase levels of information that will support the data collaboration between the smart grid components and the operational systems.

3. Do you feel that the use-case application framework is a feasible process for defining requirements and implementing interoperable topics for grid automation technologies to share and exchange on the field area network?

Answer: Yes, Challenges in the "Smart Generation" practices will benefit directly from the increase levels of interoperability among grid electrical components and different supporting technologies. The application of renewable energy systems and its challenges will benefit directly from the proposed approach.

4. Do you feel that the proposed methodology of leveraging the combination of existing standards in utility data models (e.g. CIM), MBSE tools, (e.g. UML), schemas

(IDL, XSD), and pub/sub middleware (e.g. DDS) is an effective framework for enabling interoperability for the US electric grid?

Answer: Yes. Technical, semantic and organizational levels of enterprise interoperability can be supported with the proposed methodology (see attached paper by Vernadat, 2010). MBSE tools can further support the definition of the system architecture and the interoperability characteristics of the defined "USE – CASE".

5. Can you think of any potential concerns that this interoperability framework might encounter during the development, implementation, and/or deployment processes at utility organizations?

Answer: Yes, Development, implementation and deployment processes could benefit from some sort of characterization or the interoperability concepts at different enterprise levels in the utility organization. Proper characterization of the technical, semantic and organizational levels of enterprise interoperability can support the development, implementation, and/or deployment processes at utility organizations with the proposed methodology (see attached paper by Vernadat, 2010).

Reference:

Vernadat, F, B. (2010). Technical, semantic and organizational issues of enterprise interoperability and networking. *Annual Reviews in Control volume 34.*

SURVEY RESPONSES OF R.W. NICK STAVROS, PH.D.

1. Do you believe that the lack of interoperability is a concern for the US electric grid infrastructure, either today or in the future?

Answer: Yes, The lack of interoperability is expensive to acquire, to maintain and to manage during End-of-Life transition. From an acquisition perspective, lack of interoperability often translates to loss of options during acquisition of new components. For example, there is a new device that you'd like to acquire, but you can not, because it it is not compatible with existing components. This drives new acquisition to a particular solution or at best a limited number of vendors often referred to as Vendor Lock-in. Sometimes, "bridges" or "adapters" can be used to smooth the transition, but this usually adds to the cost for acquisition. From a maintenance perspective, lack of interoperability often translates into an increase in the number of parts that need to be kept in inventory, the number of software patches that need to be applied and increased complexity of the final solution. If the components require different training, certification or tools, the problem gets worse. If a risk-of-failure is applied to each component, the more components the higher the overall risk of failure. Bridges and adapters increase the number of components and correspondingly results in more risks of failure which ultimately increases the overall cost. From and End-of-Life (EoL) perspective, the lack of interoperability can result in the need to have a "big bang" for upgrades. In other words, the upgrade requires everything in the system to be upgraded at once or to acquire temporary stopgap intermediaries such as bridges or adapters which ultimately have to be thrown away.

2. Do you believe the proposed approach of translating (via pub/sub messaging) and contextualizing information (via CIM semantic models), outside the back-office data center, is a feasible method to enable interoperability between distributed grid assets and operational systems?

Answer: Yes, the "back office" solution is hard to scale, adds costly if not potentially deadly latency, creates security vulnerabilities, and can often result in "back office" dominance in decision making. From a scalability perspective, the back office solution continuously requires more resources. Although it is possible to acquire new servers and larger networks, ultimately the solution is fragile. In the Internet-of-Things (IoT) the potential number of things far exceeds the number of people. The dramatic growth of the Internet over the last 30 years has surpassed the estimates of even the most optimistic pundits. Industry experts now predict that the number of Internet-connected devices will exceed 15

billion nodes by 2015 and top 50 billion by 2020. - See more at: http://www.electronicsweekly.com/news/business/information-technology/fifty-billion-internet-nodes-predicted-by-2020-2013-01/#sthash.piUMrkPF.dpuf

The potentially deadly latency is well documented in the slide deck in the Reference Architecture:Central Hierarchy slide. These latencies at a minimum could result in lost revenue or profits, but could result in expensive damage to the infrastructure and even potentially result in the loss of human life. If every message needs to be transmitted to a central server where a decision needs to be made and then the results of the decision need to be transmitted back to end points, at best, that is a doubling in the network traffic. How many servers and how big would the intra/internet have to be to get the latencies in the chart to those in the next chart? German Economics Minister Rainer Brüderle recently warned that Germany faces frequent power blackouts because too much 'green electricity' is being pumped onto the grid. http://www.dw.de/wind-energy-surplus-threatens-eastern-german-power-grid/a-14933985

The back office approach creates more security vulnerabilities by concentrating too much control into a single point (or perhaps a couple of points using a redundant servers). All it takes to bring down the system is to attack the back office, its power supply or its networks... referring to the revelation, in a German report released just before Christmas (.pdf), that hackers had struck an unnamed steel mill in Germany. They did so by manipulating and disrupting control systems to such a degree that a blast furnace could not be properly shut down, resulting in "massive"—though unspecified—damage

http://www.wired.com/2015/01/german-steel-mill-hack-destruction/

A botched maintenance procedure at a transmission switch yard outside Yuma touched off the blackout amid a heatwave and heavy power demands on the afternoon of Sept. 8, 2011. Over an 11 minute period, the power failure cascaded to the California coast, leaving the entire San Diego Gas & Electric service area without power as night fell.

http://www.utsandiego.com/news/2014/feb/04/violations-southwest-power-outage/

Stark's search radar and ESM systems failed to detect the incoming missiles and it was not until seconds[citation needed] before the first hit that the Americans realized they were under fire.[citation needed] The first Exocet missile tracked in

a little over 10 feet (3.0 m) above the sea surface[citation needed], and struck the port side of the ship near the bridge. Although it failed to explode, rocket fuel ignited and caused a large fire that quickly spread throughout the ship's post office, a store room, and the critical combat operations center (where the ship's weapons are controlled). The second Exocet also struck the port side. This missile did detonate, leaving a 10 ft (3.0 m) by 15 ft (4.6 m) hole in the frigate's left side. Electronics for Stark's Standard Missile defense went out and Captain Brindel could not order his men to return fire.

http://en.wikipedia.org/wiki/USS_Stark_incident.

It is often hard for Back Office decision makers to understand that increasing the size, budget and importance of the back office is not necessarily good for the company or the consumers. Back Offices are by nature centralized, server based places, so the solutions they turn to are those that are familiar to them, which is more centralization, more servers, bigger networks.

3. Do you feel that the use-case application framework is an feasible process for defining requirements and implementing interoperable topics for grid automation technologies to share and exchange on the field area network?

Answer: Yes, I wish there was more on the Platform Independent Models (PIMs) and Platform Specific Model (PSMs). These are eluded to, but not directly presented. I don't think that there is any way to proceed without adopting something very similar to this. One of the most important things for interoperability is that a single solution is not specified. For example, specifying a C# solution might only support .NET messaging or a Java solution that uses only Java Messaging Service (JMS). I understand that MQTT is a "standard", however, it is my understanding that it is primarily an IBM implementation which requires a server (IBM is after all a company that produces servers!). There are other server implementations such as RabbitMQ and Apache ActiveMQ. With that said, it is considered as one of the only ways to implement IoT by many, so it does need to be included.

4. Do you feel that proposed methodology of leveraging the combination of existing standards for the utility data models (e.g. CIM), MBSE tools, (e.g. UML), schemas (IDL, XSD), and pub/sub middleware (e.g. DDS) is an effective framework for enabling interoperability for the US electric grid?

Answer: Yes, see many of the points provided above.

5. Can you think of any potential concerns that this interoperability framework might encounter during the development, implementation, and/or deployment processes at utility organizations?

Answer: Yes, Currently, each particular electrical grid is a complex set of components that have been put together into a complex network of things. Understanding all the components, how they communicate, and how they are controlled is the specific domain of the people involved in that grid. For example, you can't just pick up a person who has worked in San Diego and move them to North Carolina and expect them to "understand" the new grid. Yes, they will have familiarity which the various components, but not in how they all fit together and perform the tasks of the grid. Consequently, there is a certain amount of security through obfuscation. As we move towards standards based solutions that are "plug-and-play", then the ability of an outsider to crack the grid is increased. This is not insurmountable, but security is even more important and needs to be baked-in at the beginning. It also means that each component needs to be smarter and react to potential threats from other components within the grid. For example, how do I isolate a malicious solar panel?

SURVEY RESPONSES OF KOSTAS TOLIOS

1. Do you believe that the lack of interoperability is a concern for the US electric grid infrastructure, either today or in the future?

Answer: Yes, ***Indeed, interoperability is achieved through harmonized standardization. Progressive Utilities have finally realized that adaption and integration of technologies that are based on interoperable standards will empower them to focus on customer services and cost effectiveness reduction schemes and less on implementing and maintaining proprietary technologies alone. Interoperability lowers the risk of system obsolescence, offers flexibility, increases supplier competition, avoids vendor lack-in, and ensures that future innovation will work across applications, platforms and networks. Currently, Utilities are trapped by Equipment Manufacturers that offer complex proprietary system and technology solutions.***

2. Do you believe that the proposed approach of translating (via pub/sub messaging) and contextualizing information (via CIM semantic models), outside the back-office data center, is a feasible method to enable interoperability between distributed grid assets and operational systems?

Answer: Yes, ***Although there are several 'proposed models' to attain end to end interoperability, the proposed ' not centralized ' approach embraces many merits. Distributed intelligence is a very promising architecture because it optimizes the transfer of 'big data' and minimizes the response time needed to control the dynamically changing power grid. The ever increasing presence of renewables and micro-grids in the distribution network necessitate local control even when the communication network is down.***

3. Do you feel that the use-case application framework is a feasible process for defining requirements and implementing interoperable topics for grid automation technologies to share and exchange on the field area network?

Answer: ***Yes, Use cases are 'story telling' processes that simply capture and describe the business requirements of how to build an interoperable framework of Smart grid technologies. Use cases have been very widely adapted by UCA, SGIP, NIST, GWAC, EPRI, ANSI, NASB, ANSI, IEC, SAE and Utilities to demonstrate how the power system grid and communication network applications work, how many systems/actors/domains are involved, and clearly***

illustrate why open standards interoperability is a major factor to making it all happen.

4. Do you feel that the proposed methodology of leveraging the combination of existing standards in utility data models (e.g. CIM), MBSE tools, (e.g. UML), schemas (IDL, XSD), and pub/sub middleware (e.g. DDS) is an effective framework for enabling interoperability for the US electric grid?

Answer: Yes, The proposed framework methodology based on existent standards, data models (CIM, UML) and schemas (IDL, XDL) has definitely great potential for adaption and future integration. The current research successfully demonstrated that, using three separate use cases with distributed architecture (DDS field message bus) that end to end interoperability was fully attainable. This is a promising and novel approach to smart grid interoperability that exposes the short comings of the traditional centralized architecture.

5. Can you think of any potential concerns that this interoperability framework might encounter during the development, implementation, and/or deployment processes at utility organizations?

Answer: Here are some potential concerns:

- ***How will you design and implement an effective" proof of concept" scalability, latency, and security testing program?***
- ***Will vendors be willing to design and support products that include proprietary core operation stack as well as the open virtual distributed operating core system?***
- ***How will the core/virtual OS be designed to ensure backward compatibility?***
- ***How will utilities and standard organizations enforce interoperability testing, compliance, certification, and device registration of vendor products?***

Some suggestions:

- ***Security shall carefully be implemented during the development of the distributed framework and not as an afterthought.***
- ***Create an Open Distributed Standards Working Group comprised of all participants (utilities and vendors and standard organizations) that are committed to open standards and interoperability implementations.***

SURVEY RESPONSES OF EVAN WALLACE

1. Do you believe that the lack of interoperability is a concern for the US electric grid infrastructure, either today or in the future?

Answer: ***Yes. Lack of interoperability on the US electric grid is a concern going forward as more dynamic energy sources and two way energy flows have to be managed and monitored to ensure safe operations while maintaining a good level of service. Data and communications will need to flow between consumers managing demand and distributed generation resources, new third party players such as energy aggregators or information brokers, and traditional stakeholders in the grid. Distribution is a key grid domain were better interoperability is needed to support these new players and new variable energy sources. This problem is challenging not only because of a large installed base of systems, equipment, and operating procedures designed to optimize availability in a relatively static environment with one way flow of energy. It's doubly challenging because the different domains in the power grid (e.g. transmission, distribution, generation, ...) have each created different standards, often in different standards organizations.***

2. Do you believe that the proposed approach of translating (via pub/sub messaging) and contextualizing information (via CIM semantic models), outside the back-office data center, is a feasible method to enable interoperability between distributed grid assets and operational systems?

Answer: ***Yes, I believe that use of a publish-subscribe API and translation (contextualizing) into a common form based on / or derived from / a "canonical information model" such as IEC CIM is a feasible method for interoperability that leverages existing standards and will support future evolution more easily (with less development cost) than other approaches.***

3. Do you feel that the use-case application framework is a feasible process for defining requirements and implementing interoperable topics for grid automation technologies to share and exchange on the field area network?

Answer: ***Yes, The use-case application framework follows best practices for software and system engineering and uses a modern model-based integration methodology and tools/standards. This is not only a feasible process for determining the correct requirements and implementing appropriate exchange***

forms providing interoperability, it is a preferred framework to meet the actual requirements while avoiding unneeded extra implementation.

4. Do you feel that the proposed methodology of leveraging the combination of existing standards in utility data models (e.g. CIM), MBSE tools, (e.g. UML), schemas (IDL, XSD), and pub/sub middleware (e.g. DDS) is an effective framework for enabling interoperability for the US electric grid?

Answer: ***Yes. An approach, such as this one, that leverages existing standards in this space is clearly the way to go in a space so crowded with existing standards. Among these standards are rich and established content model specifications for the grid (and CIM is one of the richer ones) that lend themselves to being used this way. In fact, CIM is designed to be used in model driven integration framework such as this one. This methodology will meet less resistance and require less work than defining entirely new protocols + content model specifications to support new grid interoperability. A green field approach would require a great deal more design work, be an uphill battle politically, and would require substantial additional work each time that functionality needed to be extended.***

5. Can you think of any potential concerns that this interoperability framework might encounter during the development, implementation, and/or deployment processes at utility organizations?

Answer: ***Yes. There will be major political and cultural challenges/resistance to deploying something like this that will ultimately rest some control from vendors and operators of monolithic systems presently used to collect and manage field data. However, the framework supports integrating with these existing systems. Success will require an incremental approach that proves the technologies and methodology at solving real needs in the changing power grid. The use case application framework supports such an incremental approach and the implemented system is a good start at demonstrating that this framework will work.***

SURVEY RESPONSES OF FRANK WILHOIT

1. Do you believe that the lack of interoperability is a concern for the US electric grid infrastructure, either today or in the future?

Answer: ***Yes. But lack of interoperability is merely one manifestation of a larger problem, which is that utilities generally are not good at managing the risks associated with the adoption of immature technologies. Mature technologies are interoperable, because standardized, because commoditized. Where technologies are not yet commoditized, adopters must broadly choose between two strategies: (1) embrace the heterogeneity and continuously select the least-worst; (2) predict/impose a foreseen end state post-commoditization. Interoperability can be attained, by different methods, within either of those two strategies.***

2. Do you believe that the proposed approach of translating (via pub/sub messaging) and contextualizing information (via CIM semantic models), outside the back-office data center, is a feasible method to enable interoperability between distributed grid assets and operational systems?

Answer: ***Yes, but, the question tacitly assumes strategy (2) above, where the end-state is best characterized by the adoption of a syntactic/semantic standard for information interchange. In other words, the high-value aspects of the solution are being identified with what is happening at and above layer 4 of the OSI model. However, as each layer of the OSI model depends upon the lower layers, the feasibility of the end result depends upon the fitness-for-purpose of the implementations at layers 1 through 3. The nodes of the FMB are essentially protocol adapters. As such, they are properly located within the architecture and have the right responsibilities, but they may not be able to compensate for delivered and sealed behaviors of the field equipment that they are adapting. Latency adaptation is an obvious point of risk, as well as mismatches between datagram- and connection-oriented protocols. A naive reading of the left-hand diagram of slide 8 also implies a general need to introspect any local security protocols that may have been delivered between the field equipment and its design-assumed head-end partner. So the strategy of ubiquitous adaptation is the right approach, but there is an initial increment of technological complexity and risk, until a point has been reached in the process of standardization where some of the underlying complexity can be masked off and effectively disregarded.***

3. Do you feel that the use-case application framework is a feasible process for defining requirements and implementing interoperable topics for grid automation technologies to share and exchange on the field area network?

Answer: ***Yes, consistent with the earlier observation that the diagram on slide 16 very roughly corresponds to layers 4 through 7 of the OSI model and accordingly neglects the potential impact of the lower layers. For example, a use case may tacitly assume latency that a proprietary implementation at layer 2 or 3 cannot satisfy.***

4. Do you feel that the proposed methodology of leveraging the combination of existing standards in utility data models (e.g. CIM), MBSE tools, (e.g. UML), schemas (IDL, XSD), and pub/sub middleware (e.g. DDS) is an effective framework for enabling interoperability for the US electric grid?

Answer: ***Yes. This is all implicit in the answers toquestions 2 and 3. The uptake of any such methodology will obviously depend upon the availability of a packaged toolchain, documentation, training, etc.***

5. Can you think of any potential concerns that this interoperability framework might encounter during the development, implementation, and/or deployment processes at utility organizations?

Answer: ***Quite generally, any transformation in an actor's responsibilities, or how they are discharged, is a potential point of friction. Standards are about what people have to know, but if the pain point is "too many proprietary skills", the initial introduction of candidate standards (and the tooling to manipulate them) takes that number from N to N+1, which looks like a step in the wrong direction.***

Only later does it become possible to actually reduce N. Although implementations based upon adaptation are in principle more complex, the process of building them focusses attention on the standards under adoption; even any deep study of the proprietary implementations that may be necessary along the way is slanted towards understanding in terms of the standards at the semantic level.

SURVEY RESPONSES OF PAMELA WISE-MARTINEZ

1. Do you believe that the lack of interoperability is a concern for the US electric grid infrastructure, either today or in the future?

Answer: Yes, the lack of interoperability for the US electric grid infrastructure is a major concern, technical and cultural challenge. The US electric grid is unable to support the today information sharing needs about the field issues, as well as not being able to support the future large-scale needs of renewable energy products and services.

2. Do you believe that the proposed approach of translating (via pub/sub messaging) and contextualizing information (via CIM semantic models), outside the back-office data center, is a feasible method to enable interoperability between distributed grid assets and operational systems?

Answer: Yes, the approach is. The average person thinks of the grid as well-integrated and well-managed architecture, and do not understand the limitations and issues with sustainability and access. The proposed approach moves the challenge of fractured, proprietary hardware and lack of interoperability to a field bus approach that supports as true integrated, near-real-time, self-healing distributed messaging architecture.

3. Do you feel that the use-case application framework is a feasible process for defining requirements and implementing interoperable topics for grid automation technologies to share and exchange on the field area network?

Answer: Yes, the use-case application framework supports a great way to define requirements for Field Area Network. This will help implementers to address usages, and shared requirements for the Field Message Bus.

4. Do you feel that the proposed methodology of leveraging the combination of existing standards in utility data models (e.g. CIM), MBSE tools, (e.g. UML), schemas (IDL, XSD), and pub/sub middleware (e.g. DDS) is an effective framework for enabling interoperability for the US electric grid?

Answer: Yes, I believe is this use of combining the right standards, at the right architecture layer makes this not only doable but a sound methodology. This addresses traffic prioritization and response time.

5. Can you think of any potential concerns that this interoperability framework might encounter during the development, implementation, and/or deployment processes at utility organizations?

Answer: the potential challenge that this reference implementation might encounter during the development is the systemic culture issues from the vendor, policy makers and appropriate regulatory and law making bodies for concept adoption, and implementation. The technology and approaches aren't hugely novel in that, ESB's have solved distributed architecture issues for many years, and standardized API's concepts are nearly 15 years embedded in large scale systems integrations.

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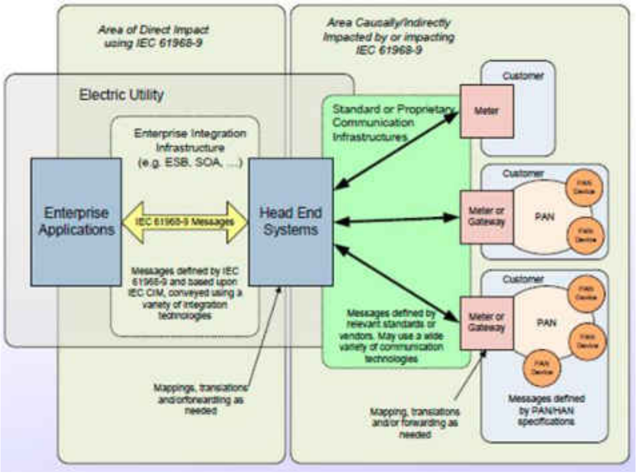

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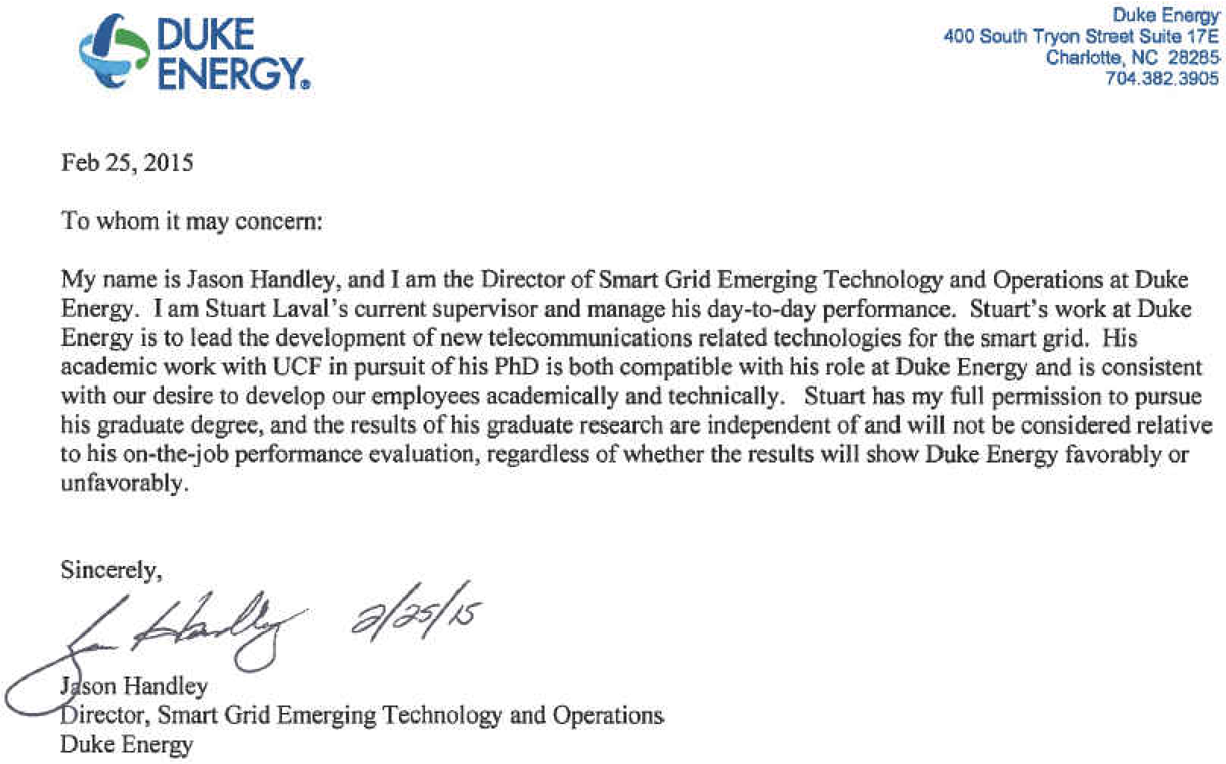

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Feb 25, 2015

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My name is Jason Handley, and I am the Director of Smart Grid Emerging Technology and Operations at Duke Energy. I am Stuart Laval's current supervisor and manage his day-to-day performance. Stuart's work at Duke Energy is to lead the development of new telecommunications related technologies for the smart grid. His academic work with UCF in pursuit of his PhD is both compatible with his role at Duke Energy and is consistent with our desire to develop our employees academically and technically. Stuart has my full permission to pursue his graduate degree, and the results of his graduate research are independent of and will not be considered relative to his on-the-job performance evaluation, regardless of whether the results will show Duke Energy favorably or unfavorably.

Sincerely,

2/25/15

Jason Handley
Director, Smart Grid Emerging Technology and Operations
Duke Energy

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