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CYBER-PHYSICAL SECURITY OF AN ELECTRIC MICROGRID

by

PRASHANTH PALANISWAMY

A THESIS

Presented to the Graduate Faculty of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

in

COMPUTER SCIENCE

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Approved by

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## ABSTRACT

Cyber-physical systems (CPSs) are physical systems that are controlled or monitored by computer-based systems. CPSs are a combination of computation, networking, and physical processes. As CPSs are a combination of various diverse components, they are vulnerable to several security threats. Moreover, there are many different security domains (not just high/low, nor necessarily hierarchical). This paper utilizes previously developed multiple security domain nondeducibility (MSDND) to uncover potential integrity vulnerabilities in an electric microgrid. Invariants are manually generated using the insights obtained through MSDND analysis and use linear regression to automate the generation of invariants. The vulnerabilities are then mitigated, to the extent possible, by adding executable invariants on system operation. Implementation on the Electric Power and Intelligent Control (EPIC) testbed at the Singapore University of Technology and Design is reported. Limitations of the design and successes/shortcomings of attack mitigation are reported.

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## NOMENCLATURE

### Greek

- $\oplus$  Exclusive OR (xor)
- $\epsilon$  random error or residual in linear regression
- $\phi$  A boolean statement that can be evaluated

### Subscripts

- $W$  The set of all possible worlds of the system
- $SD^i$  Represents the security domain with respect to  $i$
- $w$  A world of interest
- $s_x$  A boolean state variable,  $x$  is true or false
- $B_i \phi$  Modal BELIEF operator
- $I_{i,j} \phi$  Modal INFORMATION TRANSFER operator
- $T_{i,j} \phi$  Modal TRUST operator
- $RPM$  revolutions per minute of AC motor
- $RR$  Relay readings
- $CD$  Batteries charging/discharging percentage
- $CBS$  Circuit breaker status
- $CBC$  Circuit breaker command

$V$	Voltage reading from Relay
$i$	Current reading from Relay
$f$	Frequency reading from smart meter
$fR$	Frequency reading from Relay
$P$	Power reading from Relay
$V_x^y$	valuation function of boolean $x$ in domain $y$

## 1. INTRODUCTION

Cyber-physical systems (CPS) are smart systems that include engineered interacting networks of physical and computational components. One of the significant requirements of a CPS is to be resilient (NIS, 2017). The next generation CPS must be resilient to correlated threats (threats in which more than one attacker acts on an entity) where simple perimeter protections are not sufficient. As such, CPSs need to be looked at in a different light, one in which multiple components exist and sometimes overlap containing entities that interact with each other. Figure 1.1 shows the basic architecture of an electric smart grid with multiple interacting components (FitzPatrick and Wollman, 2010).

In such architectures, transmission must interact with distribution, markets, service providers, operations, and, increasingly, customers through information exchange and computation in addition to the transfer of the commodity - power.

Classical models do not capture this well; within the context of an electric power system, a subset of domains can be categorized into two primary types of entities, control centers and business networks activities. Within the control centers, energy management and Supervisory control and data acquisition (SCADA) systems control/read from remote terminal units (RTUs) which, in turn, control/read from sensors and actuators. The control center must also interact with peer control centers, potentially not in the same organization. The classical hierarchical model of Biba (Bishop, 2003) forces the arrangement of security partitions into just the two (McMillin and Roth, 2017) seen in a modern electric utility, essentially that the business enterprise of a utility cannot write up into the control system, by placing the control system at a higher security level; this prevents a potential virus that has compromised the business enterprise from impacting with the control system as

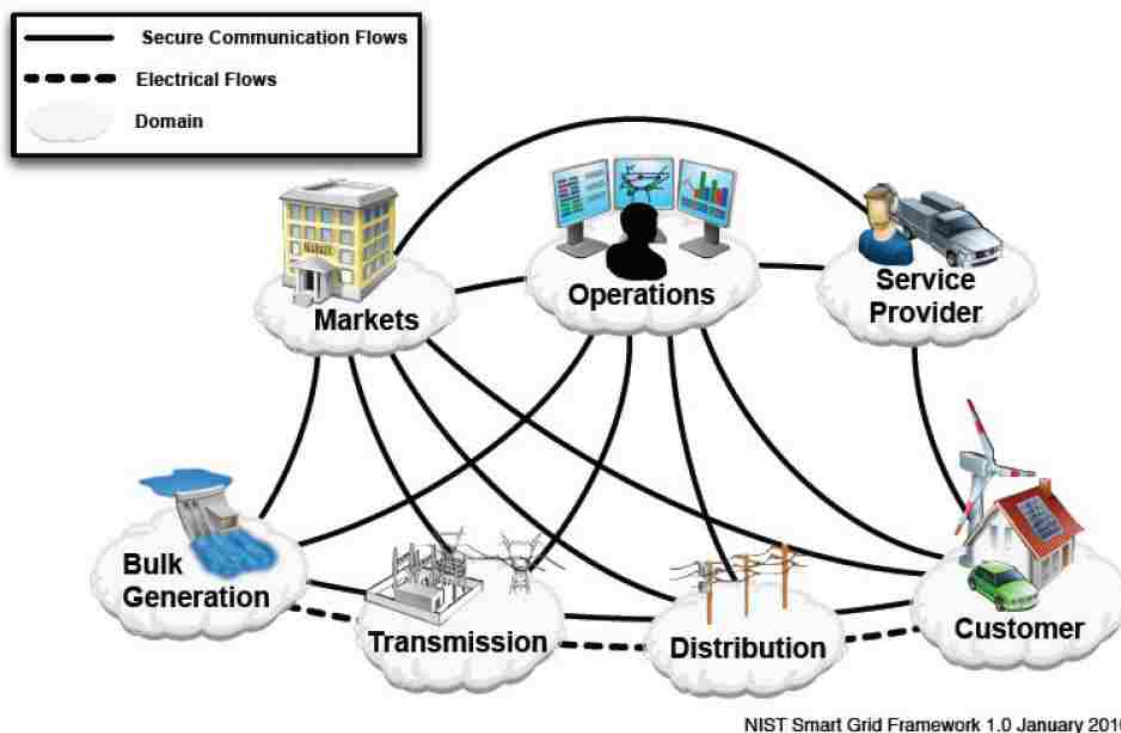


Figure 1.1. Electric Distribution System Architecture (FitzPatrick and Wollman, 2010)

shown in Figure 1.2. Unfortunately, it does not prevent attacks coming from cyber or physical components within the security domain and perimeter defenses cannot secure these components as it would disrupt the normal information flow within the power grid.

In this document, we examine the general security concerns of an electric grid through a testbed instantiation using Design-centric approach (DeC) and Data-centric approach (DaC). The DeC approach uses Multiple Security Domains Nondeducibility (MS-DND) (Howser and McMillin, 2014) (Howser and McMillin, 2013) models and Belief, Information transfer and Trust (BIT) logic (Liau, 2003) (Liau, 2005) to address the issues of vulnerabilities within this multi-domain environment by making use of manually designed invariants. The DaC approach makes use of the machine learning algorithm- Linear regression (Lin, 1997) to automate invariant generation. The invariants generated from two methods are then evaluated for their efficiency in identifying faults/attacks in the system.

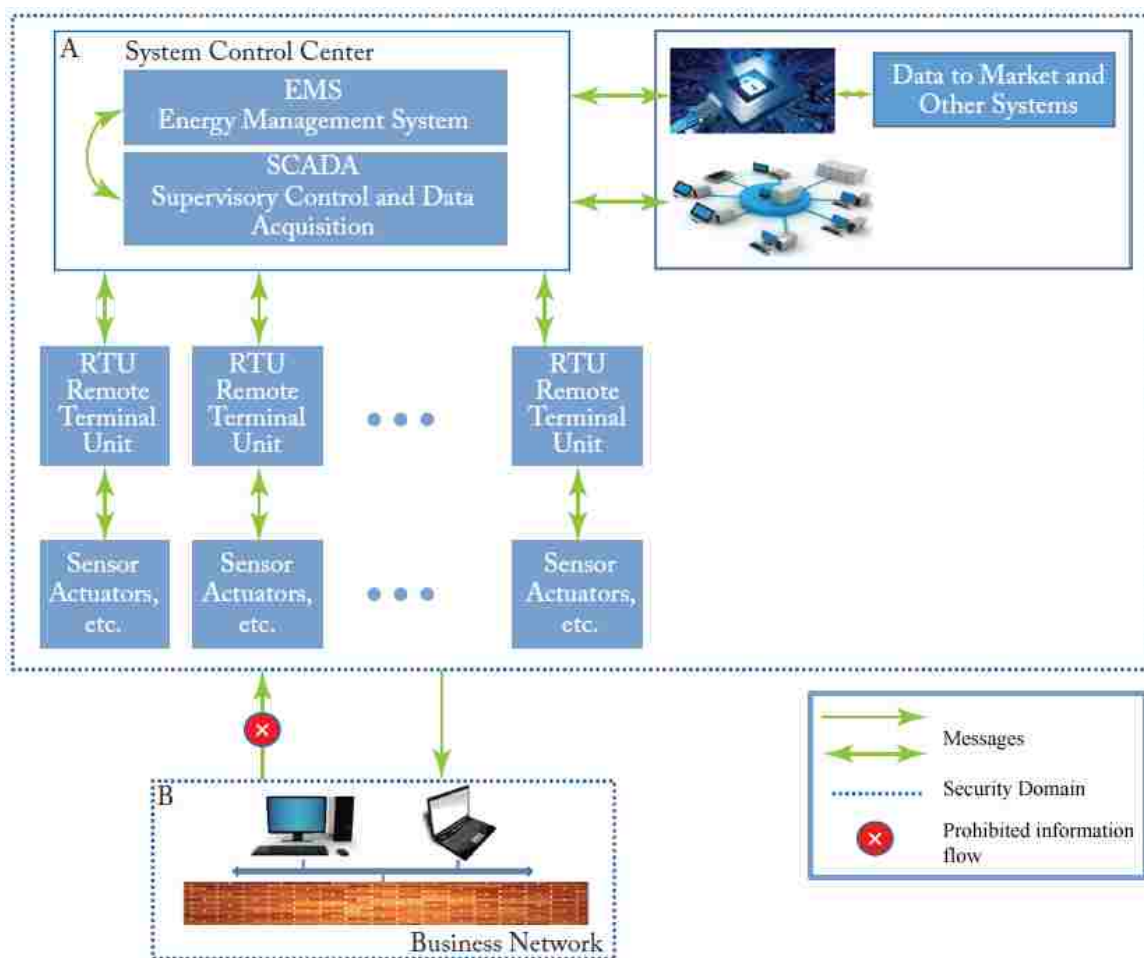


Figure 1.2. Biba Model of an Electric Power System (McMillin and Roth, 2017)

**Thesis outline.** This thesis is organized as follows, Section 2 explains the different approaches, models that are used for vulnerability analysis and invariant generation, and the model of a microgrid. Section 3 explains the problem statement, Section 4 describes the work that has been done related to this problem, Section 5 analyses the vulnerabilities. Section 6 describes mathematical methods for security analysis, mitigations to the potential threats and those threats that cannot be mitigated due to design restrictions, and invariant generation. Section 7 explains the results, Section 8 presents concluding remarks and Section 9 outlines future work.

## 2. BACKGROUND

### 2.1. APPROACHES

**2.1.1. Design-centric Approach (DeC).** In DeC, the CPS are analyzed for vulnerabilities and attack detection methods are generated manually based on the physics of the system.

**2.1.1.1. Nondeducibility (ND) (Sutherland, 1986).** Nondeducibility approach models the information flow between the different partitions in a system. Partitions are usually created within the system based on functionality. The system partitions are normally termed as high and low and are separated from each other. If the information in one partition is not deductible at the other, then they are nondeducibility secure with each other. The partitions in ND model are absolute and simple. If the partitions overlap as in the case of critical infrastructure like industrial control systems, then the ND model does not have the required features to model the information flow. To address this MSDND model was developed which has better control over the information being transferred.

**2.1.1.2. Valuation function.**  $V_x^y(\phi)$  represents the valuation function the domain  $y$  has about the state  $x$ . The valuation function assigns a Boolean value to the question  $\phi$  based on the status of  $x$  with respect to the security domain  $y$ .

**2.1.1.3. Security domain ( $SD^i$ ) (Howser and McMillin, 2013).** The system is split into several security domains  $SD^i$  as observed by each entity  $i$  in the system by the event system. The domains might overlap or be disjoint with respect to each other. An entity  $i$  in a system is a component that can perform action or observation on its own.



**2.1.1.4. Multiple security domain nondeducibility .** MSDND does not partition the system into just high and low, but instead, it partitions into domains which can be overlapping, disjoint or wholly contained in other domains. From one security domain if we do not have valuation function to determine the state of the other domain, then these two domains are said to be MSDND secure with each other.

Formally the MSDND model can be defined as, ‘There exists some world with a pair of states where one must be true and the other false (exclusive OR), but an entity  $i$  has no valuation function for those states. In security domain  $SD^i$ ,  $i$  simply cannot know which state is true and which is false’ (Howser and McMillin, 2013).

$$\text{MSDND(ES): } \exists w \in \mathbf{W} \vdash [(s_x \vee s_y)] \wedge \sim(s_x \wedge s_y) \wedge [w \models (\nexists V_x^i(w) \wedge \nexists V_y^i(w))]$$

An equivalent formula is,

$$\text{MSDND(ES): } \exists w \in \mathbf{W} \vdash [(s_x \oplus s_y)] \wedge [w \models (\nexists V_x^i(w) \wedge \nexists V_y^i(w))]$$

In the confidentiality aspect, MSDND secure information path is good for the system and in the integrity aspect, an MSDND secure information path is bad for the system (Dunaka and McMillin, 2017). For example, when a burglar enters a house, the owner should know about the intrusion (integrity). On the other hand, a burglar outside the house should not know whether the owner is present in the house or not (confidentiality).

MSDND analysis helps in identifying information paths that are vulnerable to integrity attacks and provides insights for creating invariants, which can help in enhancing the resiliency of a CPS.

**2.1.1.5. BIT logic.** BIT logic is an approach to formally define the belief, information transfer and trust of cyber systems. Initially it was used for handling trust in software systems (Liau, 2003) (Liau, 2005). If there are human interactions involved, then BIT logic is effective to use in CPS as well. Spoofing in the system can be well explained using formal proofs that utilizes BIT logic. The belief and trust that an entity  $i$  has in information from

an entity  $j$  can be reasoned using BIT logic. BIT Logic makes use of three new modal operators to describe what entities believe, trust, and communicate with each other, they are:

- $T_{i,j} \phi$  - trust that domain  $i$  has on report from domain  $j$ , when  $j$  tells that  $\phi$  is true
- $B_i \phi$  - belief that domain  $i$  has on information  $\phi$ ; regardless of  $\phi$ 's value,  $i$  always believes  $\phi$  to be true
- $I_{i,j} \phi$  - transfer of information from domain  $j$  to  $i$  that the value  $\phi$  is true

**2.1.2. Data-centric Approach (DaC).** In DaC, the system is operated for a considerable period of time in different use cases and data is collected from them. The collected data is used to train a suitable machine learning algorithm and rules (invariants) which always hold true throughout the system operation are extracted from it. These invariants when implemented in the system would notify the operator when there is something abnormal with the system.

**Linear regression.** With an assumption of a linear relationship between dependent variable ( $Y$ ) and independent variable ( $X$ ), linear regression represents the relationship with a best fitting linear model calculated with observed data. A population linear regression model can be interpreted as,

$$Y = aX + b + \epsilon$$

Where,  $a$  is the population slope, also called regression coefficient;  $b$  is the population y-intersection, and  $\epsilon$  is the random error or residual (Lin, 1997). With linear regression, significant independent predictors can be identified, and outliers can be detected with a specific threshold.

## 2.2. APPLICATION: ELECTRIC SMART GRID

Electric Power and Intelligent Control (EPIC) is one of the four testbeds at iTrust (iTrust, 2016), which is a center for research in cybersecurity that strengthens the infrastructure available to researchers in cybersecurity, and is located at the Singapore University of Technology and Design (SUTD). EPIC is a power testbed, and it comprises four stages: Generation, Transmission, Micro-grid, and Smart Home.

The Generation stage consists of a power source from SUTD's grid and three generators. The three generators are rated at 10 kW each and provide a total of 30 kW of maximum power. At the transmission stage, an autotransformer is used to step up or step down the voltage to the smart home or micro-grid. The smart home consists of two load banks with programmable variable resistive, inductive, and capacitive loads. The micro-grid consists of 110 photovoltaic cells (PV) and two sets of batteries. One battery is a backup for the PV in case of cloud cover, and the other battery is 5 kW and is used to supply power to SCADA in case of a complete blackout to carryout load shedding. PV cells along with the first set of batteries produce a total power of 34 kW. Power management between the PV cells and the battery, and the battery charging/discharging percentage is controlled by a SMA cluster controller. Figure 2.1 shows the EPIC testbed with electric components.

Smart meters with advanced metering infrastructure (AMI) obtain readings of voltages, current, power factor, and power consumption and are installed at several locations throughout the EPIC grid. Readings from individual meters can be viewed via a web-based workstation, and the readings from the SCADA are recorded through Historian, which is a database software application that logs time-based process data. Historian, AMI, and SCADA run on different machines as shown in Figure 2.2. SCADA and Historian are in the same network, but AMI is in a different network.

Examples of critical information:

- Revolutions per minute (RPM): The RPM of the motor plays a key role in the power grid system. It determines the voltage and frequency of the generated electricity. The RPM value is regulated by the device called the variable speed drive (VSD). VSD also provides the RPM values to the SCADA.
- Relay reading (RR): The RR from the IED/Relay contains the readings of voltage, current, frequency, and power of the line in which the relay is present:

$$RR = (V, i, fR, P); \quad (2.1)$$

where  $V$ -voltage,  $i$ -current,  $fR$ -frequency, and  $P$ -power.

For normal operation of EPIC, frequency should be 50 Hz and flow voltage should be 415 V, with an allowed deviation of  $\pm 6\%$ . If the frequency or voltage is above or below the threshold, then the relay would send commands to trip the circuit breaker.

- Battery charging/discharging rule (CD) in percentage: The battery level percentage at which the battery should only undergo charging and the percentage at which it can discharge are set at the cluster controller. CD plays an important role in maintaining health of the battery and having backup power in times of need.
- Circuit breaker status (CBS): The status of the circuit breaker determines whether or not there will be flow of electricity further down the system. CBS is sent from the relay to the control system.
- Circuit breaker command (CBC): The instruction for opening or closing the circuit breaker sent from the control system to the circuit breaker. Before passing the CBC from the control system, the relay modifies or simply transfers the CBC to the circuit breaker based on the flow voltage.

Each of the critical information pieces have an information path associated with them.

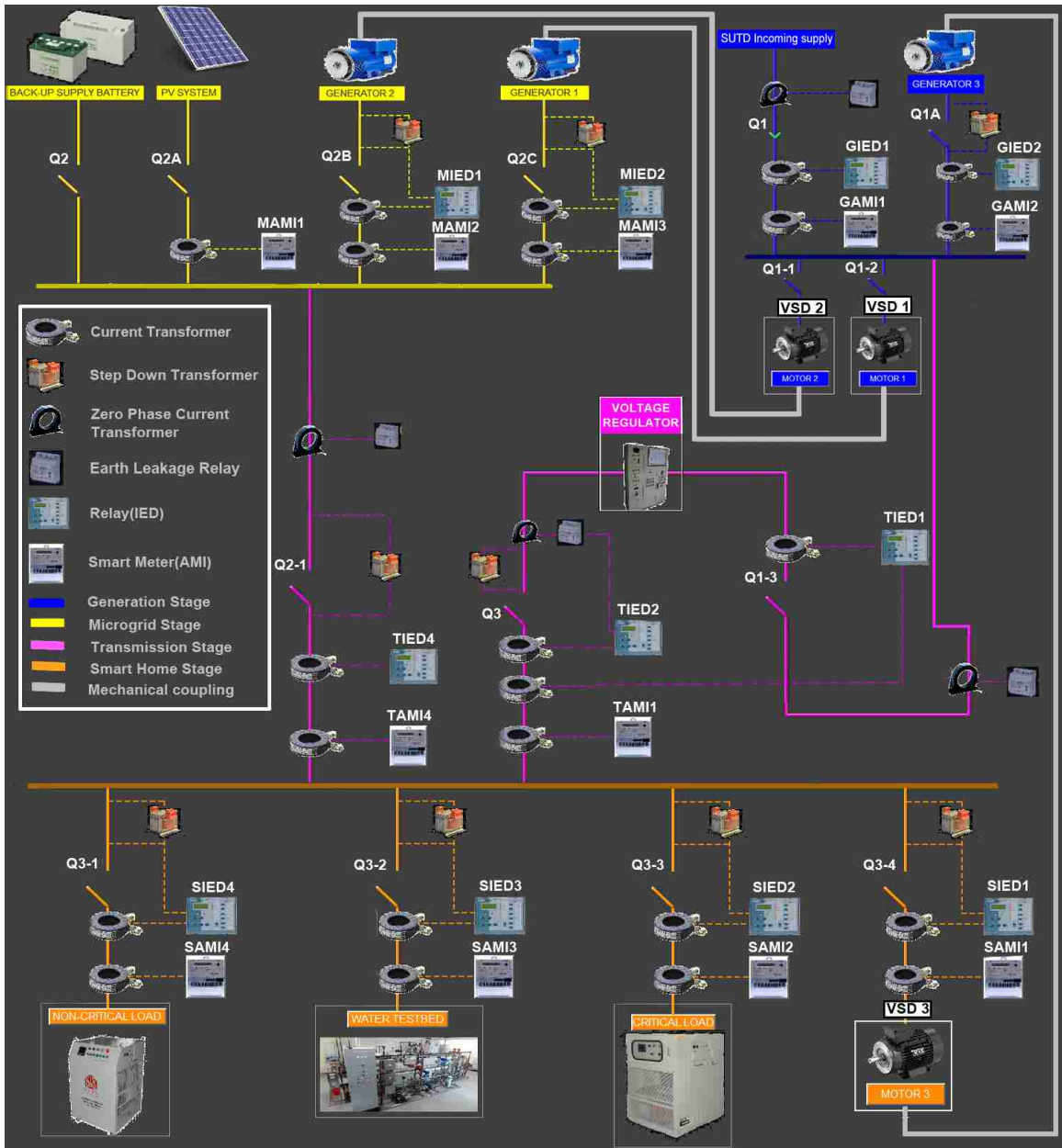


Figure 2.1. EPIC- Single Line Diagram

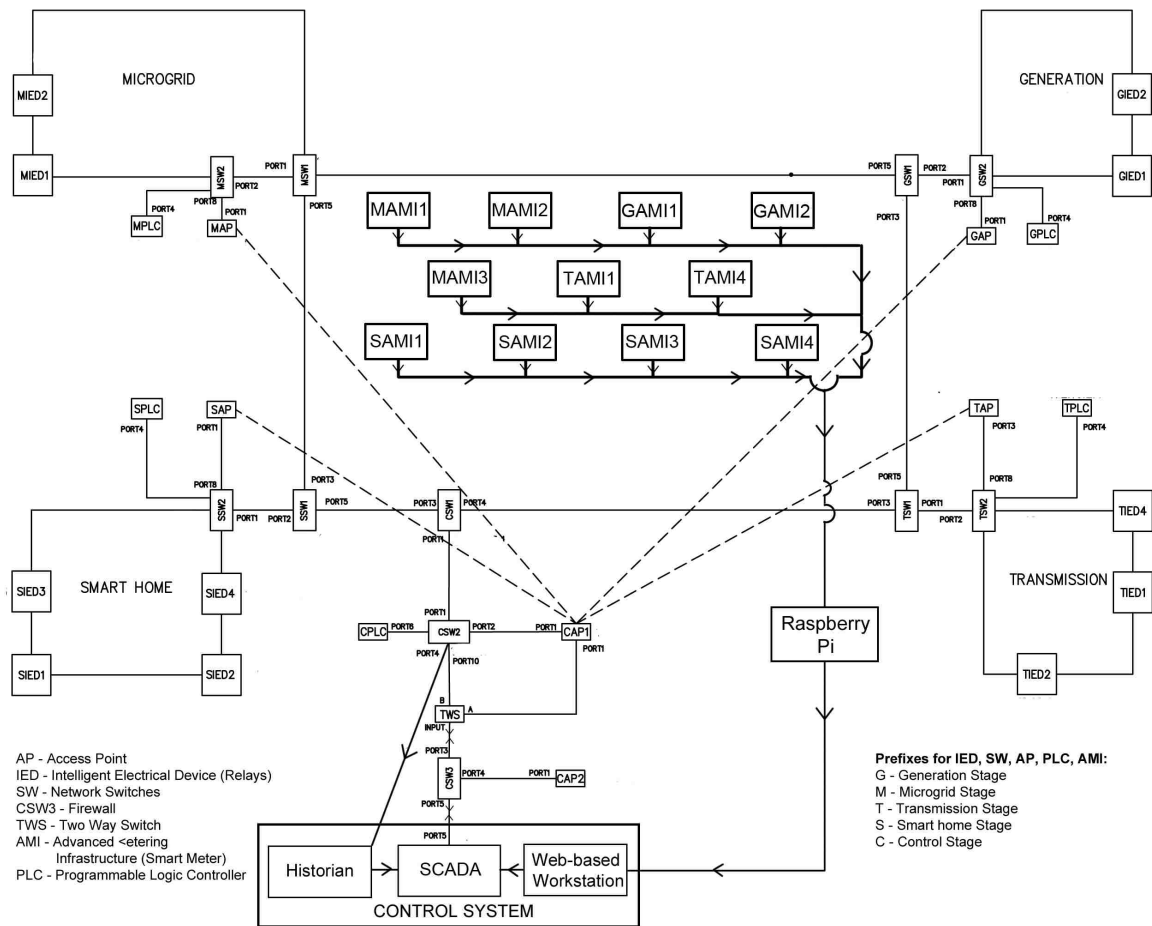


Figure 2.2. EPIC- Network Diagram (iTrust, 2016). Examples for interpreting the devices from diagram: i) MAMI2 - Microgrid stage Smart meter, device 2, ii) TIED4 - Transmission stage Relay, device 4.

### 3. PROBLEM STATEMENT

Power grids are the most critical infrastructure of all countries. Power grids nowadays are largely smart and have many devices installed throughout the system to enable easy operation and monitoring, which makes them more prone to cyber attacks. Cyber attacks on such a critical CPS can cause a major disaster to a nation and have a serious impact on its economy. In most of these attacks, the attacker has a good understanding of the various devices in the CPS and designs malware for them. This malware carries out a man-in-the-middle attack that fakes process control sensor signals so an infected system does not shut down due to detected abnormal behavior. The malware also modifies the data sent to the control system to make it look normal. So, there is no way for the operator to know that the CPS is under attack. An attack of this kind happened in Iran (Falliere *et al.*, 2011). In this case, the Stuxnet was executed from the Siemens PLC and varied the centrifuge's rotor speed between high and low continuously in an attempt to damage the centrifuge. The Stuxnet also sent recorded false positive reports that indicated normal rotor speeds back to human operators. Because of this, the attack was undetected and many centrifuges were damaged. In 2016, a malware caused a power outage for about an hour in Ukraine that affected more than tens of thousands of households. The malware was found to be capable of launching automated assaults against industrial control systems managing the electric grid.

In this thesis, a model-based approach is carried out to find the vulnerable information paths in the system. Invariants were generated through DeC and DaC methods and implemented in the control system to identify Stuxnet-like attacks and abnormalities in a smart grid.

## 4. VULNERABILITY ANALYSIS

In this thesis, a Stuxnet-like attack model is assumed in an electric microgrid. The goal of these attacks is to disrupt system operation by confusing the system through deception.

### 4.1. ATTACK MODEL

Stuxnet-like worms are malicious codes that can be injected into a system through USB flash drives, shared networks, etc. Once Stuxnet is injected, it replicates to spread and hides by faking a healthy working condition of the system. To do this, the worm targets SCADA systems. In specific, it gets access to the programmable logic controller (PLC), infects it with harmful operational commands and returns previously recorded normal feedbacks to devices (sym, 2010). The undetectable mechanism of a Stuxnet-like worm makes use of the security vulnerability of a system along with rootkits to make the attack hard to be identified (Mueller and Yadegari, 2012). If an observer does not have valuation function to ascertain whether the state of the system is true or false, then the system is secure with respect to integrity. The operator cannot deduce if there is any fault or attack in the system. Thus, secure paths within a system are bad.

### 4.2. INVARIANTS

An invariant is a logical predicate on system state and its truth value must not change if it is satisfied by system execution. It is a property, function or quantity that stays unchanged whilst a stated transformation is applied. Invariants were initially created for cyber systems (Owicki and Gries, 1976). Lately, invariants have also been extended for CPSs like power systems (Gamage *et al.*, 2015) (Paul *et al.*, 2014) and water treatment



systems (Adepu and Mathur, 2016). Defining invariants for CPSs are much harder than in cyber processes because it requires a thorough understanding of the working of physical and cyber components in the system.

The invariant equations in the EPIC testbed are executed at the control system. Coupling MSDND and the invariant equations, the bounds on parameters measured in a power grid can be minimized and the corrupt information path can be identified with a better precision.

## 5. RELATED WORK

An attestation framework that makes use of physical process constraints as invariants was proposed (Roth and McMillin, 2016) to validate behaviors and identify attacks in cyber-physical systems, in particular, a smart power grid. In the paper, false injection attacks are concentrated as a typical attack method that commonly used against a smart grid. There exist malicious cyber injection attacks that are proven to be hidden from pure software detection. In such cases, physical verification plays an important role in exhibiting faulty behaviors in the system.

The authors introduced a signature-based invariant protocol, 7-node attestation, which is based on a manually summarized violation pattern on the law of the conservation of energy. It examines neighboring household power migrations and setup invariants calculated with actual power flow parameters, such as voltages and phase angles. Both current measurements and saved conservations of such parameters are involved in the computation of the invariant between a set of smart nodes. Under the proclaimed framework, a fake supply attack where a malicious supplier pretends to increase the generation power to meet the demand but actually violates the protocol can be deduced. Although the framework introduced the physical layer attestation, due to the limitation of the invariant, a malicious participant can be located only over specific topologies. It will also not work in network partitions, which have limited communication between nodes.

MSDND approach helps in identifying integrity attacks within a system and has been used in modeling security for several other cyber physical infrastructures like air traffic control systems (Thudimilla and McMillin, 2017), chemical plants (Dunaka and McMillin, 2017) and vehicle platoon systems (Kanteti, 2017).

## 6. SECURITY ANALYSIS AND INVARIANT GENERATION

### 6.1. DESIGN-CENTRIC APPROACH

**MSDND Analysis.** In MSDND analysis, the information flow paths of different critical information pieces in the system are analyzed in the proofs using BIT logic. Mathematical analysis of each piece of information is performed from the source to the destination (control system) through different security domains in which the information gets passed. The point at which the information can get corrupted is identified, and invariants are generated to create a valuation function that helps detect the attack.

There are five different types of critical information in the testbed, as seen in Section 2.2. Each type of critical information has an information path associated with it. The security domains for each of the information paths is shown in Figures 6.1, 6.2, 6.3 and 6.4. In the following proofs, invariants are used to break the MSDND security of an integrity attack.

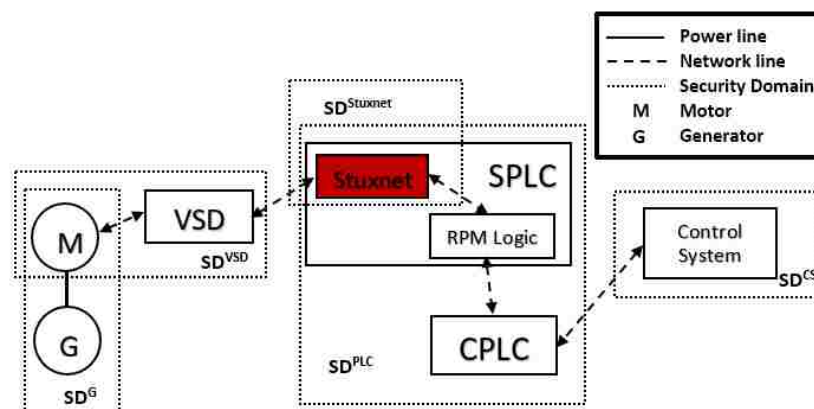


Figure 6.1. Security domains of 'RPM' information path

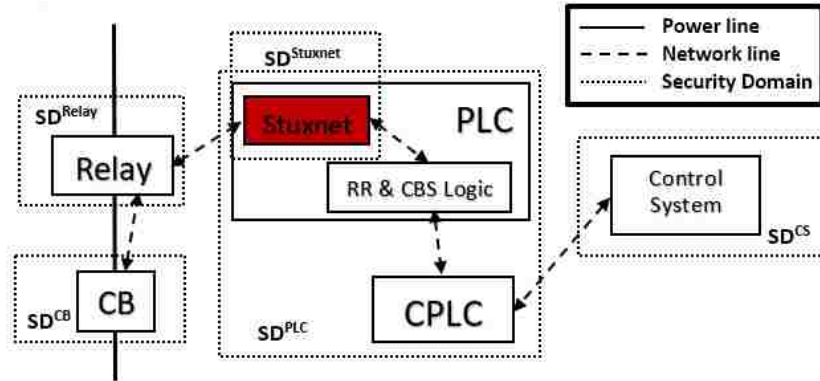


Figure 6.2. Security domains of 'RR and CBS' information path

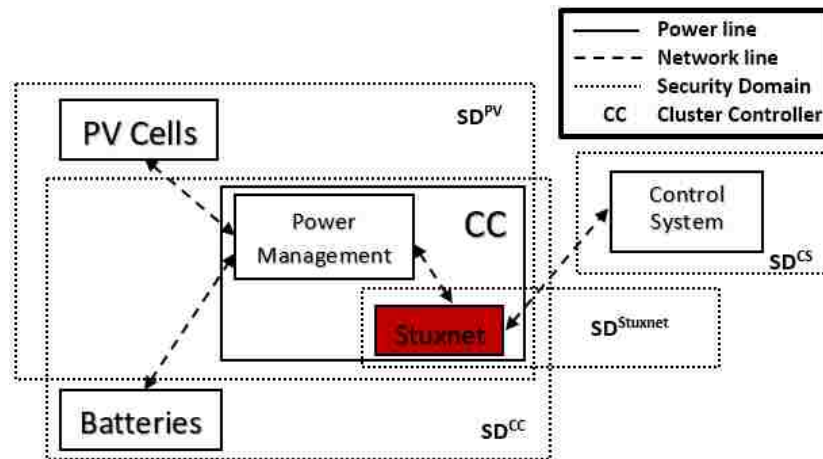


Figure 6.3. Security domains of 'CD' information path

**Assumption.**  $RR$  contains various values as mentioned in Equation 2.1. For a successful attack, the attacker needs to change all the values in  $RR$  proportionately. This assumption has been used in the DeC approach for generating invariants. Only the frequency values are considered in generating the invariant. If the frequency of  $RR$  fails the invariant equation, then the other values will also fail.

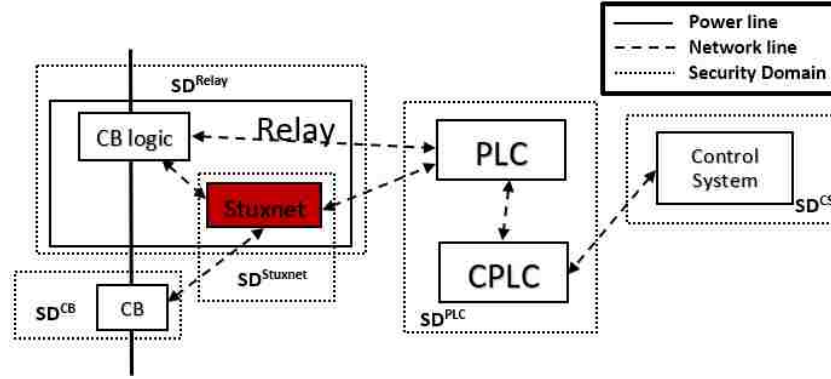


Figure 6.4. Security domains of 'CBC' information path

**Macros.** The following macro is used in the theorems defined below.,

$IBT_{1,2}Val = I_{1,2}Val$ ; /\*2 reported to 1 that  $Val$  is true\*/

$B_1I_{1,2}Val$ ; /\*1 believes that  $Val$  is true\*/

$T_{1,2}Val$ ; /\*The trust that 1 has on 2 about the information  $Val$ \*/

$B_1I_{1,2}Val \wedge T_{1,2}Val \rightarrow B_1Val$ ; /\*1 believes that  $Val$  is correct\*/

- **Single-point attacks**

*Analysis of vulnerability in RPM information path.*

**Theorem 1.** *The RPM reading  $RPM$  from VSD is MSDND secure at the Control System (CS) when  $RPM$  is not normal but the reading is normal.*

*Proof.* Here the  $RPM$  reading from VSD is modified by the Stuxnet and sent to the CS.

1.  $\sim RPM = \text{true}$ ; The  $RPM$  is not normal
2.  $w \models V_{\sim RPM}^{VSD}(w) = \text{true}$ ;  $RPM$  reading is not normal at the VSD
3.  $IBT_{Stuxnet, VSD} \sim RPM$ ; Stuxnet intercepts the abnormal  $RPM$  sent by VSD to PLC
4.  $w \models V_{\sim RPM}^{Stuxnet}(w) = \text{true}$ ; Stuxnet observes that  $RPM$  is abnormal

5.  $IBT_{PLC,Stuxnet} RPM$ ; Stuxnet modifies  $RPM$  to make it look normal and sends it to PLC and PLC believes it
6.  $w \models V_{RPM}^{PLC}(w) = \text{true}$ ;  $RPM$  appears normal in PLC world
7.  $IBT_{CS,PLC} RPM$ ; PLC tells CS that  $RPM$  is normal and CS believes it
8.  $w \models V_{RPM}^{CS}(w) = \text{true}$ ; CS believes that  $RPM$  is normal, it does not have valuation function to verify it
9. MSDND(ES):  $\exists w \in W \vdash [(S_{RPM} \oplus S_{\sim RPM})] \wedge [w \models (\nexists V_{\sim RPM}^{CS}(w) \wedge \nexists V_{RPM}^{CS}(w))]$

The CS believes the false positive  $RPM$  reading reported by the Stuxnet and believes that everything is normal. Therefore  $RPM$  information is MSDND secure from the CS. There are three such MSDND secure paths in the system as shown in Table 6.1.  $\square$

**Theorem 2.** *The  $RPM$  reading  $RPM$  from VSD is not MSDND secure when  $RPM$  is not normal but the reading is normal and an invariant on the frequency  $f$  and  $RPM$  are considered.*

*Proof.* Let us assume the frequency reading  $f$  from the AMI is correct. Let the invariant  $iRPM: RPM = 30f$  be in the control system. The invariant is derived from the equation,  $RPM = \frac{(120 \times f)}{P}$ , where  $P$  is the number of poles in the motor, here  $P = 4$ .

1.  $\sim RPM = \text{true}$ ; The  $RPM$  is not normal
2.  $w \models V_{\sim RPM}^{VSD}(w) = \text{true}$ ;  $RPM$  reading is not normal at the VSD
3.  $IBT_{Stuxnet,VSD} \sim RPM$ ; Stuxnet intercepts the abnormal  $RPM$  sent by VSD to PLC
4.  $w \models V_{\sim RPM}^{Stuxnet}(w) = \text{true}$ ; Stuxnet observes that  $RPM$  is abnormal
5.  $IBT_{PLC,Stuxnet} RPM$ ; Stuxnet modifies  $RPM$  to make it look normal and sends it to PLC and PLC believes it

Table 6.1. Summary of MSDND analysis for RPM information path

S.No.	MSDND Secure Paths	Invariant Available
1	VSD1→SPLC→CPLC→CS	Yes
2	VSD2→SPLC→CPLC→CS	Yes
3	VSD3→SPLC→CPLC→CS	Yes

6.  $w \models V_{RPM}^{PLC}(w) = \text{true}$ ;  $RPM$  appears normal in PLC world
7.  $IBT_{CS,PLC} RPM$ ; PLC tells CS that  $RPM$  is normal and CS believes it
8.  $\sim RPM \implies \sim f$ ; when  $RPM$  is not normal it affects the  $RR$
9.  $IBT_{CS,AMI} \sim f$ ; CS obtains the  $f$  reading from smart meter and believes it
10.  $\sim iRPM \implies \sim RPM$ ; from our assumption that the frequency reading  $f$  from the AMI is correct and the invariant  $iRPM$ , the CS deduces that  $RPM$  is not normal
11.  $(S_{iRPM}, S_{RPM}) = S''$ ; System is working normally if and only if  $S''$  is true
12.  $w \models V_{\sim RPM}^{CS}(w) = \text{true}$ ; CS now has deduced that  $RPM$  is abnormal
13.  $\sim \text{MSDND(ES)}$ :  $\exists w \in W \vdash [(S'' \oplus S_{\sim RPM})] \wedge [w \models (\exists V_{\sim RPM}^{CS}(w) \wedge \nexists V_{RPM}^{CS}(w))]$

The system is not MSDND secure as we have valuation function for normal working of the system as shown in Figure 6.5, and fault/threat can be detected. This can be used to break three MSDND secure paths in the system.  $\square$

*Analysis of vulnerability in CD information path.*

**Theorem 3.** *The battery charging/discharging percentage CD set at the cluster controller (CC) is MSDND secure at the control system (CS)*

*Proof.* 1.  $\sim CD = \text{true}$ ; charging/discharging percentage set is not normal

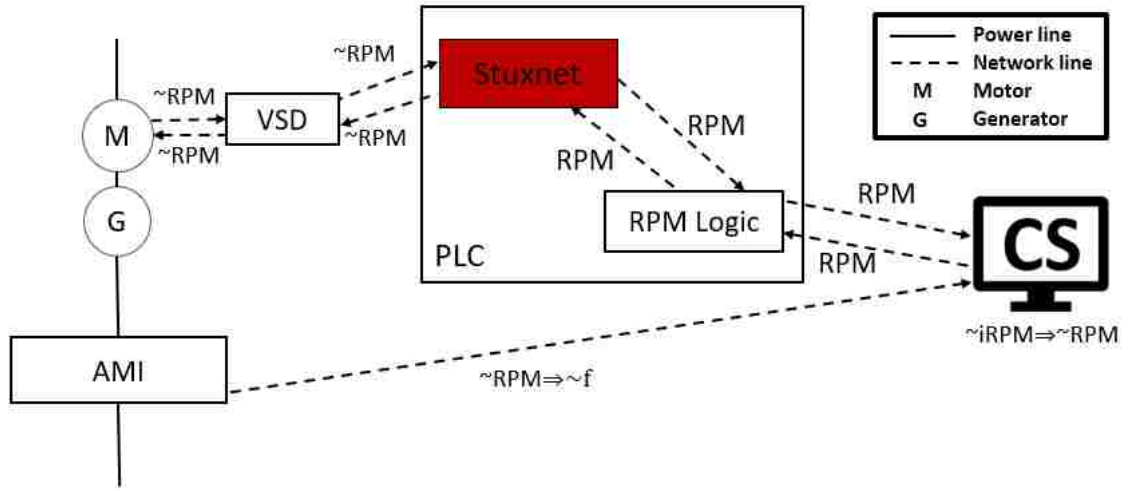


Figure 6.5. Information flow when  $RPM$  is abnormal and invariant is used. Attack model for this is explained in Theorem 1 and attack detection is explained in Theorem 2.

2.  $w \models V_{\sim CD}^{CC}(w) = \text{true}$ ;  $CD$  is not normal in  $CC$  world
3.  $IBT_{Stuxnet,CC} \sim CD$ ; Stuxnet intercepts the abnormal  $CD$  sent by Cluster controller to CS
4.  $w \models V_{\sim CD}^{Stuxnet}(w) = \text{true}$ ; Stuxnet observes that  $CD$  is abnormal
5.  $IBT_{CS,Stuxnet} CD$ ; Stuxnet reports that the  $CD$  is normal to CS and CS believes it
6.  $w \models V_{CD}^{CS}(w) = \text{true}$ ; CS believes  $CD$  to be normal
7.  $MSDND(ES): \exists w \in W \vdash [(S_t \oplus S_{\sim t})] \wedge [w \models (\nexists V_{\sim CD}^{CS}(w) \wedge \nexists V_{CD}^{CS}(w))]$

The control system believes that battery charging/discharging level set in the cluster controller is in desired range. The  $CD$  cannot be evaluated at the CS and hence it is MSDND secure. Moreover, there are no alternate information paths to define invariant for this path as seen in Figure 6.6. □



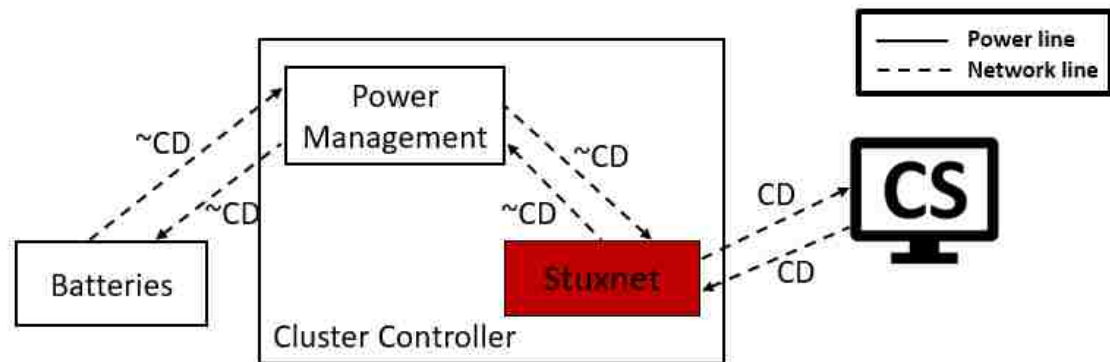


Figure 6.6. Information flow when  $CD$  is abnormal. Attack model for this is explained in Theorem 3.

*Analysis of vulnerability in RR information path.*

**Theorem 4.** *RR (within threshold or not) information is MSDND secure when the flow voltage is normal but the circuit breaker trips*

*Proof.* Here, the voltage that flows through the relay is within threshold but still the circuit breaker is tripped, i.e.,  $CBS = \text{open}$ .

1.  $fV = \text{true}$ ; The flow voltage is within threshold
2.  $w \models V_{fV}^{Relay}(w) = \text{true}$ ; The relay observes that the voltage is normal
3.  $fV \implies CBS$ ; When the flow voltage is normal, the relay sends the CB the same command that SCADA sends to CB, so here it directs CB to remain closed
4.  $CBS = \text{true}$ ;  $CBS$  is normal
5.  $w \models V_{CBS}^{Relay}(w) = \text{true}$ ;  $CBS$  is normal in relay world
6.  $IBT_{Stuxnet,Relay} CBS$ ; Stuxnet intercepts the normal  $CBS$  sent by Relay to CB
7.  $w \models V_{CBS}^{Stuxnet}(w) = \text{true}$ ; Stuxnet observes that  $CBS$  is normal

8.  $IBT_{CB,Stuxnet} \sim CBS$ ; The Stuxnet instructs the CB to open even though the flow voltage is normal
9.  $CBS = \text{open} \implies RR = 0$ ; When CB is open the relay reading is zero
10.  $\sim RR = \text{true}$ ;  $RR$  is now not normal
11.  $w \models V_{\sim RR}^{Relay}(w) = \text{true}$ ; Relay observes that  $RR$  is not normal
12.  $IBT_{PLC,Relay} \sim RR$ ; Relay tells PLC that  $RR$  is not normal and PLC believes it
13.  $w \models V_{\sim RR}^{PLC}(w) = \text{true}$ ;  $RR$  is not normal in PLC world
14.  $IBT_{CS,PLC} \sim RR$ ; PLC tells CS that  $RR$  is not normal and CS believes it
15.  $w \models V_{\sim RR}^{CS}(w) = \text{true}$ ;  $RR$  is abnormal in CS, CS believes it is because of abnormal flow voltage
16. MSDND(ES):  $\exists w \in W \vdash [(S_{RR} \oplus S_{\sim RR})] \wedge [w \models (\nexists V_{\sim RR}^{CS}(w) \wedge \nexists V_{RR}^{CS}(w))]$

The  $RR$  reading received at the CS are all zero hence it is not possible to deduce at the CS whether the CB trip was because of voltage beyond threshold or because of fault/attack. Hence, the system is MSDND secure. There are eleven such MSDND secure paths in the system as listed in the Table 6.3.  $\square$

**Theorem 5.**  *$RR$  (within threshold or not) information is not MSDND secure if the invariant is used when the flow voltage is normal but the circuit breaker trips*

*Proof.* Here the  $CBS = \text{open}$  and hence  $RR=0$ . To check whether the trip was because of fault/attack we take the readings  $pRR$  from the Relays that are present immediately before the relay that got tripped. Table 6.2 lists the relay readings that need to be used for each of the relays that has zero reading because of tripping. If two relays are listed then any one of them that does not have zero reading can be used.  $Proj_{pFR}(pRR) = pFR$ . Let us assume

Table 6.2. Relay association with previous closest relays

Relay with zero reading	Relay reading to use
GIED1	Not available
GIED2	SIED1
TIED1	GIED1/GIED2
TIED2	TIED1
TIED4	MIED1/MIED2
MIED1	GIED1/GIED2
MIED2	GIED1/GIED2
SIED1	TIED2/TIED4
SIED2	TIED2/TIED4
SIED3	TIED2/TIED4
SIED4	TIED2/TIED4

the frequency reading  $pFR$  from the closest previous relay is accurate. Let the invariant  $iFThresh : 47 < pFR < 53$  be in the control system. The normal operating frequency of the EPIC system is 50 Hz with an allowed deviation of  $\pm 6\%$ .

1.  $fV = \text{true}$ ; The flow voltage is within threshold
2.  $w \models V_{fV}^{Relay}(w) = \text{true}$ ; The relay observes that the voltage is normal
3.  $fV \implies CBS$ ; When the flow voltage is normal, the relay sends the CB the same command that SCADA sends to CB, so here it directs CB to remain closed
4.  $CBS = \text{true}$ ;  $CBS$  is normal
5.  $w \models V_{CBS}^{Relay}(w) = \text{true}$ ;  $CBS$  is normal in relay world
6.  $IBT_{Stuxnet,Relay} CBS$ ; Stuxnet intercepts the normal  $CBS$  sent by Relay to CB
7.  $w \models V_{CBS}^{Stuxnet}(w) = \text{true}$ ; Stuxnet observes that  $CBS$  is normal
8.  $IBT_{CB,Stuxnet} \sim CBS$ ; The Stuxnet instructs the CB to open even though the flow voltage is normal

9.  $CBS=open \implies RR=0$ ; When CB is open  $RR$  is zero
10.  $\sim RR = true$ ;  $RR$  is now not normal
11.  $w \models V_{\sim RR}^{Relay}(w) = true$ ; Relay observes that  $RR$  is not normal
12.  $IBT_{PLC,Relay} \sim RR$ ; Relay tells PLC that  $RR$  is not normal and PLC believes it
13.  $w \models V_{\sim RR}^{PLC}(w) = true$ ;  $RR$  is not normal in PLC world
14.  $IBT_{CS,PLC} \sim RR$ ; PLC tells CS that  $RR$  is not normal and CS believes it
15.  $w \models V_{\sim RR}^{CS}(w) = true$ ;  $RR$  is abnormal in the CS world, CS believes it is because of abnormal flow voltage
16.  $IBT_{PLC,Relay} pRR$ ;  $pRR$  is extracted from previous closest relay to the relay in which zero reading was shown
17.  $w \models V_{pRR}^{PLC}(w) = true$ ;  $pRR$  is normal in PLC world
18.  $IBT_{CS,PLC} pRR$ ; PLC tells CS that  $pRR$  is normal and CS believes it
19.  $iFThresh \implies pFR \implies RR$  ( $\because Proj_{pFR}(pRR) = pFR$ ); From our assumption that the frequency reading  $pFR$  from the closest previous relay is accurate and the invariant  $iFThresh$ , the CS deduces that  $RR$  is normal
20.  $S'' = (S_{iFThresh}, S_{RR})$ ; System is working normally if and only if  $S''$  is true
21.  $w \models V_{RR}^{CS}(w) = true$ ;  $RR$  is normal in the CS world
22.  $\sim MSDND(ES): \exists w \in W \vdash [(S'' \oplus S_{\sim RR})] \wedge [w \models (\exists V_{\sim RR}^{CS}(w) \wedge \nexists V_{RR}^{CS}(w))]$

When the  $RR$  reading received at the CS are all zero but  $pRR$  readings are all within threshold during this period, then we can deduce that the trip in the CB was not because of abnormal flow voltage, but because of fault/attack. Hence, the system is no longer MSDND

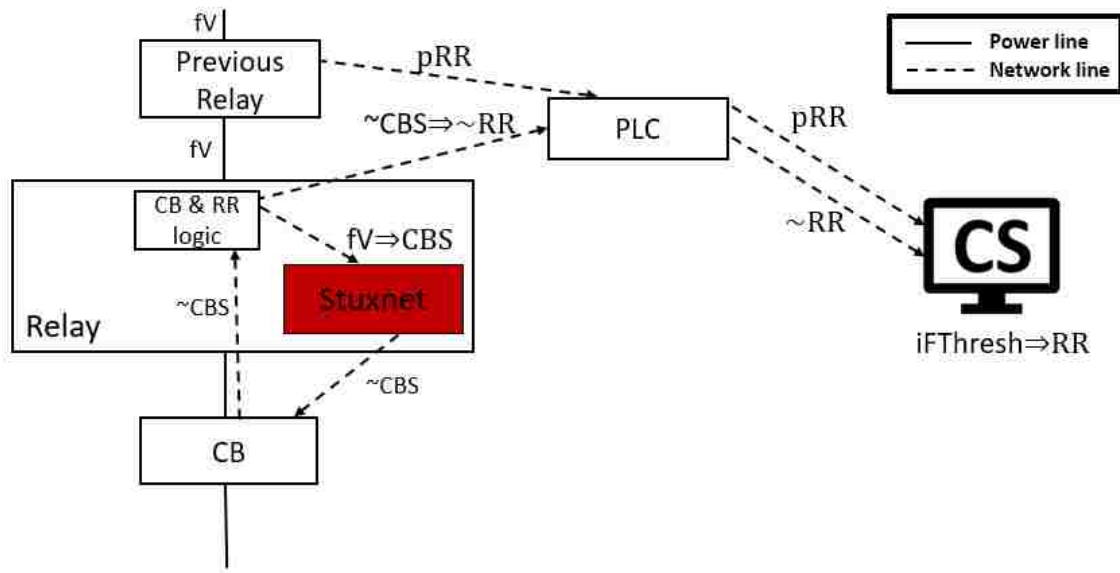


Figure 6.7. Information flow when  $RR$  is normal but the  $CB$  trips, and invariant is considered. Attack model for this is explained in Theorem 4 and attack detection is explained in Theorem 5.

secure as seen in Figure 6.7. This theorem can be used to break ten MSDND secure paths out of the eleven. The MSDND secure path when GIED1  $RR$  shows zero can not be broken, because there are no relays present before it. This is a design flaw in the system.  $\square$

**Theorem 6.**  $RR$  (within threshold or not) information is MSDND secure when the flow voltage is abnormal but the circuit breaker does not trip

*Proof.* Here the voltage that flows through the relay is not within threshold, but the circuit breaker does not trip, i.e.,  $CBS = \text{closed}$ . The Stuxnet changes the circuit breaker command sent from the relay to the  $CB$  (i.e., open to closed) and masks the  $RR$  sent from the relay to the  $CS$ .

1.  $\sim fV = \text{true}$ ; The flow voltage is not within threshold
2.  $w \models V_{\sim fV}^{Relay}(w) = \text{true}$ ; The relay observes that the voltage is not within threshold

3.  $\sim fV \implies \sim CBS$ ; When the flow voltage is not normal, the relay ignores the SCADA command to CB and directs it to open
4.  $\sim CBS = \text{true}$ ;  $CBS$  at relay is different from  $CBS$  at SCADA
5.  $w \models V_{\sim CBS}^{Relay}(w) = \text{true}$ ;  $CBS$  is not normal at the relay
6.  $IBT_{Stuxnet,Relay} \sim CBS$ ; Stuxnet intercepts the abnormal  $CBS$  sent by relay to CB
7.  $w \models V_{\sim CBS}^{Stuxnet}(w) = \text{true}$ ; Stuxnet knows that the  $CBS$  is not normal
8.  $IBT_{CB,Stuxnet} CBS$ ; Stuxnet modifies the  $CBS$  and instructs the CB that it is normal, CB believes it
9.  $\sim fV \implies \sim RR$ ; The flow voltage is not normal so that reflects  $RR$
10.  $\sim RR = \text{true}$ ;  $RR$  is not normal
11.  $w \models V_{\sim RR}^{Relay}(w) = \text{true}$ ;  $RR$  is abnormal in relay world
12.  $IBT_{Stuxnet,Relay} \sim RR$ ; Stuxnet intercepts the abnormal  $RR$  sent by relay to CB
13.  $w \models V_{\sim RR}^{Stuxnet}(w) = \text{true}$ ; Stuxnet observes that  $RR$  is abnormal
14.  $IBT_{PLC,Stuxnet} RR$ ; Stuxnet modifies  $RR$  to make it look normal and transmits it to PLC and PLC believes it
15.  $w \models V_{RR}^{PLC}(w) = \text{true}$ ;  $RR$  looks normal in PLC world
16.  $IBT_{CS,PLC} RR$ ; PLC tells CS that  $RR$  is normal and CS believes it
17.  $w \models V_{RR}^{CS}(w) = \text{true}$ ; CS believes that  $RR$  is normal and system is normally working
18. MSDND(ES):  $\exists w \in W \vdash [(S_{RR} \oplus S_{\sim RR})] \wedge [w \models (\nexists V_{\sim RR}^{CS}(w) \wedge \nexists V_{RR}^{CS}(w))]$

The  $RR$  readings received at the CS are all normal as the Stuxnet had sent false positives. Hence, it is not possible to deduce at the CS whether the  $RR$  is within threshold or not. Thus, the system is MSDND secure. There are eleven such MSDND secure paths in the system as listed in Table 6.3.  $\square$

**Theorem 7.** *The Relay reading  $RR$  (within threshold or not) information is not MSDND secure when the flow voltage is abnormal but the circuit breaker does not trip if the invariants are considered.*

*Proof.* Let us assume the frequency reading  $f$  from the AMI is correct. Let  $fR$  be the frequency reading from the relay. Let the invariant  $iFreq : f == fR$  and  $47 < f < 53$  be in the CS.

1.  $\sim fV = \text{true}$ ; The flow voltage is not within threshold
2.  $w \models V_{\sim fV}^{Relay}(w) = \text{true}$ ; The relay observes that the voltage is not within threshold
3.  $\sim fV \implies \sim CBS$ ; When the flow voltage is not normal, the relay ignores the SCADA command to CB and directs it to open
4.  $\sim CBS = \text{true}$ ;  $CBS$  at relay is different from  $CBS$  at SCADA
5.  $w \models V_{\sim CBS}^{Relay}(w) = \text{true}$ ;  $CBS$  is not normal at the relay
6.  $IBT_{Stuxnet,Relay} \sim CBS$ ; Stuxnet intercepts the abnormal  $CBS$  sent by relay to CB
7.  $w \models V_{\sim CBS}^{Stuxnet}(w) = \text{true}$ ; Stuxnet knows that the  $CBS$  is not normal
8.  $IBT_{CB,Stuxnet} CBS$ ; Stuxnet modifies the  $CBS$  and instructs the CB that it is normal, CB believes it
9.  $\sim fV \implies \sim RR$ ; The flow voltage is not normal so that reflects  $RR$
10.  $\sim RR = \text{true}$ ;  $RR$  is not normal

11.  $w \models V_{\sim RR}^{Relay}(w) = \text{true}$ ;  $RR$  is abnormal in relay world
12.  $IBT_{Stuxnet,Relay} \sim RR$ ; Stuxnet intercepts the abnormal  $RR$  sent by relay to CB
13.  $w \models V_{\sim RR}^{Stuxnet}(w) = \text{true}$ ; Stuxnet observes that  $RR$  is abnormal
14.  $IBT_{PLC,Stuxnet} RR$ ; Stuxnet modifies  $RR$  to make it look normal and transmits it to PLC and PLC believes it
15.  $w \models V_{RR}^{PLC}(w) = \text{true}$ ;  $RR$  looks normal in PLC world
16.  $IBT_{CS,PLC} RR$ ; PLC tells CS that  $RR$  is normal and CS believes it
17.  $\sim fV \implies \sim f$ ; When  $fV$  is abnormal, even the AMI readings are abnormal
18.  $IBT_{CS,AMI} \sim f$ ; CS obtains the  $f$  reading from AMI and believes it
19.  $\sim iFreq \implies \sim fR \implies \sim RR$  ( $\because \text{Proj}_{fR}(RR) = fR$ ); From our assumption that the frequency reading  $f$  from the AMI is correct and the invariant  $iFreq$ , the CS deduces that  $RR$  is abnormal
20.  $S'' = (S_{invariant}, S_{RR})$ ; System is working normally if and only if  $S''$  is true
21.  $w \models V_{\sim RR}^{CS}(w) = \text{true}$ ; CS with help of invariant knows that  $RR$  is not normal
22.  $\sim \text{MSDND}(\text{ES}): \exists w \in W \vdash [(S'' \oplus S_{\sim RR})] \wedge [w \models (\exists V_{\sim RR}^{CS}(w) \wedge \nexists V_{RR}^{CS}(w))]$

When the frequency reading from the AMI and relay does not match, and when the frequency reading from the AMI is not within threshold, then we can deduce at the CS that the  $RR$  was not within threshold, but still the relay did not trip. This is demonstrated in Figure 6.8. Thus, the system is not MSDND secure. Using this invariant, all the eleven such MSDND secure paths in the system listed in Table 6.3 can be broken, including the path involving GIED1. □



Table 6.3. Summary of MSDND analysis for RR information path

S.No.	MSDND Secure Paths	Invariant Available
1	GIED1→GPLC→CPLC→CS	No
2	GIED2→GPLC→CPLC→CS	Yes
3	MIED1→MPLC→CPLC→CS	Yes
4	MIED2→MPLC→CPLC→CS	Yes
5	TIED1→TPLC→CPLC→CS	Yes
6	TIED2→TPLC→CPLC→CS	Yes
7	TIED4→TPLC→CPLC→CS	Yes
8	SIED1→SPLC→CPLC→CS	Yes
9	SIED2→SPLC→CPLC→CS	Yes
10	SIED3→SPLC→CPLC→CS	Yes
11	SIED4→SPLC→CPLC→CS	Yes

*Analysis of vulnerability in CBS information path.*

**Theorem 8.** *The Circuit breaker status CBS is MSDND secure at the CS when the CB is open but SCADA shows it as closed and also when the CB is closed but SCADA shows it as open.*

*Proof.* Here the Stuxnet changes the true value of the CBS. It changes it from true to false or from false to true.

1.  $CBS = \text{true}$ ; CBS is normal
2.  $w \models V_{CBS}^{CB}(w) = \text{true}$ ; CBS is normal in CB world
3.  $IBT_{Relay,CB} CBS$ ; CB tells relay that CBS is normal and Relay believes it
4.  $w \models V_{CBS}^{Relay}(w) = \text{true}$ ; CBS is normal in relay world
5.  $IBT_{PLC,Relay} CBS$ ; relay tells PLC that CBS is normal and PLC believes it
6.  $w \models V_{CBS}^{PLC}(w) = \text{true}$ ; CBS is normal in PLC world
7.  $IBT_{Stuxnet,PLC} CBS$ ; Stuxnet intercepts the normal CBS sent by PLC to CS

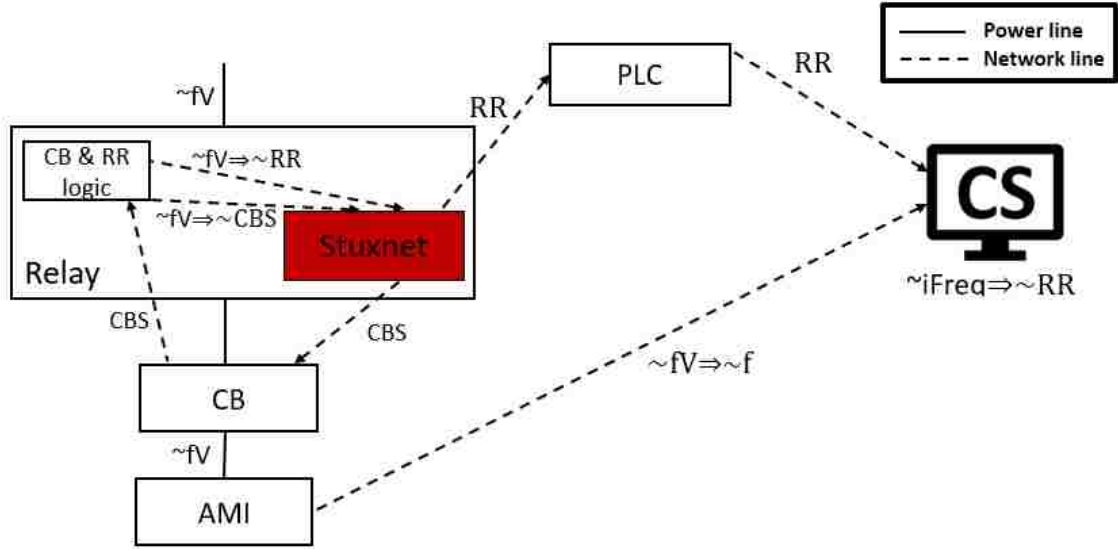


Figure 6.8. Information flow when  $RR$  is abnormal but  $CB$  does not trip, and invariant is considered. Attack model for this is explained in Theorem 6 and attack detection is explained in Theorem 7.

8.  $\sim CBS = \text{true}$ ; The Stuxnet reverses the  $CBS$  from the original status
9.  $w \models V_{\sim CBS}^{Stuxnet}(w) = \text{true}$ ; The Stuxnet knows that it has altered the  $CBS$  from its original status
10.  $IBT_{CS,Stuxnet} CBS$ ; Stuxnet reports the CS that the  $CBS$  is normal and CS believes it
11.  $w \models V_{\sim CBS}^{CS}(w) = \text{false}$ ; CS does not know that  $CBS$  is not normal
12.  $MSDND(ES): \exists w \in W \vdash [(S_{CBS} \oplus S_{\sim CBS})] \wedge [w \models (\nexists V_{\sim CBS}^{CS}(w) \wedge \nexists V_{CBS}^{CS}(w))]$

The Stuxnet modifies the actual  $CBS$  received from the PLC and sends a false value to the CS and the CS believes it to be the true state of the CB. Hence, it is not possible to deduce at the CS whether the  $CBS$  is correct or not. Thus, the system is MSDND secure. There are thirty such MSDND secure paths in the system, fifteen when the CB is open and the SCADA shows it as closed, and fifteen when the CB is closed and the SCADA shows it as open. There are two possible cases for each of the listed paths in Table 6.4.  $\square$

**Theorem 9.** *CBS is not MSDND secure at the CS when the CB is open but SCADA shows it as closed if the invariant is taken into consideration.*

*Proof.* Let us assume that the relay reading  $RR$  is correct. Let  $fR$  be the frequency reading from the relay. Let the invariant  $iCBClosedCheck : CBS == closed \text{ and } fR \neq 0$  be in the CS

1.  $CBS = true$ ;  $CBS$  is normal and its value is open
2.  $w \models V_{CBS}^{CB}(w) = true$ ;  $CBS$  is normal in CB world
3.  $IBT_{Relay,CB} CBS$ ; CB tells relay that  $CBS$  is normal and relay believes it
4.  $w \models V_{CBS}^{Relay}(w) = true$ ;  $CBS$  is normal in relay world
5.  $IBT_{PLC,Relay} CBS$ ; relay tells PLC that  $CBS$  is normal and PLC believes it
6.  $w \models V_{CBS}^{PLC}(w) = true$ ;  $CBS$  is normal in PLC world
7.  $IBT_{Stuxnet,PLC} CBS$ ; Stuxnet intercepts the normal  $CBS$  sent by PLC to CS
8.  $\sim CBS = true$ ; The Stuxnet changes the  $CBS$  status as closed from open
9.  $w \models V_{\sim CBS}^{Stuxnet}(w) = true$ ; The Stuxnet knows that it has altered the  $CBS$  from its original status
10.  $IBT_{CS,Stuxnet} CBS$ ; The Stuxnet reports the CS that the  $CBS$  is open and it is normal
11.  $w \models V_{\sim CBS}^{CS}(w) = false$ ; CS does not know that  $CBS$  is not normal
12.  $RR = true$ ;  $RR$  is normal
13.  $w \models V_{RR}^{Relay}(w) = true$ ;  $RR$  is normal in relay world
14.  $IBT_{PLC,Relay} RR$ ; relay tells PLC that  $RR$  is normal and PLC believes it
15.  $w \models V_{RR}^{PLC}(w) = true$ ;  $RR$  is normal in PLC world

16.  $IBT_{CS,PLC}RR$ ; PLC tells CS that  $RR$  is normal and CS believes it
17.  $w \models V_{RR}^{CS}(w) = \text{true}$ ;  $RR$  is normal in CS world
18.  $Proj_{fR}(RR) = fR, \sim iCBClosedCheck \implies \sim CBS$ ; when the invariant  $iCBClosedCheck$  fails, CS deduces that  $CBS$  is not normal
19.  $w \models V_{\sim CBS}^{CS}(w) = \text{true}$ ; CS world now has deduced that  $CBS$  is abnormal
20.  $S'' = (S_{iCBClosedCheck}, S_{CBS})$ ; System is working normally if and only if  $S''$  is true
21.  $\sim \text{MSDND}(\text{ES}): \exists w \in \mathbf{W} \vdash [(S'' \oplus S_{\sim CBS})] \wedge [w \models (\exists V_{\sim CBS}^{CBS}(w) \wedge \nexists V_{CBS}^{CS}(w))]$

When the CB is closed, the  $fR$  should not be zero, if  $fR$  is zero then that indicates that the  $CBS$  at the CS is not correct. Hence, the system is no longer MSDND secure. This is demonstrated in Figure 6.9. This theorem can be used to break twelve MSDND secure paths in the system out of the fifteen as shown in Table 6.4. The three CB Q1-1, Q1-2 and Q2 does not have a relay or a smart meter next to them to validate their state through this invariant.

**Note:** For the circuit breaker Q2A there are no relays next to it, we make use of the frequency reading from the AMI in the invariant  $iCBClosedCheck$  instead of  $fR$ .  $\square$

**Theorem 10.** *The Circuit breaker state  $CBS$  is not MSDND secure at the CS when the CB is closed but SCADA shows it as open if the invariant is taken into consideration.*

*Proof.* Let us assume that the relay reading  $RR$  is correct. Let  $fR$  be the frequency reading from the relay. Let the invariant  $iCBOpenCheck : CBS == \text{open and } fR = 0$  be in the CS

1.  $CBS = \text{true}$ ;  $CBS$  is normal and its value is closed
2.  $w \models V_{CBS}^{CB}(w) = \text{true}$ ;  $CBS$  is normal in CB world

Table 6.4. Summary of MSDND analysis for CBS information path

S.No.	MSDND Secure Paths	Invariant Available
1	Q1→GIED1→GPLC→CPLC→CS	Yes
2	Q1A→GIED2→GPLC→CPLC→CS	Yes
3	Q1-1→GPLC→CPLC→CS	No
4	Q1-2→GPLC→CPLC→CS	No
5	Q2→MPLC→CPLC→CS	No
6	Q2A→MPLC→CPLC→CS	Yes
7	Q2B→MIED1→MPLC→CPLC→CS	Yes
8	Q2C→MIED2→MPLC→CPLC→CS	Yes
9	Q1-3→TIED1→TPLC→CPLC→CS	Yes
10	Q3→TIED2→TPLC→CPLC→CS	Yes
11	Q2-1→TIED4→TPLC→CPLC→CS	Yes
12	Q3-4→SIED1→SPLC→CPLC→CS	Yes
13	Q3-3→SIED2→SPLC→CPLC→CS	Yes
14	Q3-2→SIED3→SPLC→CPLC→CS	Yes
15	Q3-1→SIED4→SPLC→CPLC→CS	Yes

3.  $IBT_{Relay,CB}$  *CBS*; CB tells relay that *CBS* is normal and relay believes it
4.  $w \models V_{CBS}^{Relay}(w) = \text{true}$ ; *CBS* is normal in relay world
5.  $IBT_{PLC,Relay}$  *CBS*; relay tells PLC that *CBS* is normal and PLC believes it
6.  $w \models V_{CBS}^{PLC}(w) = \text{true}$ ; *CBS* is normal in PLC world
7.  $IBT_{Stuxnet,PLC}$  *CBS*; Stuxnet intercepts the normal *CBS* sent by PLC to CS
8.  $\sim CBS = \text{true}$ ; The Stuxnet changes the *CBS* status as open from closed
9.  $w \models V_{\sim CBS}^{Stuxnet}(w) = \text{true}$ ; The Stuxnet knows that it has altered the *CBS* from its original status
10.  $IBT_{CS,Stuxnet}$  *CBS*; The Stuxnet reports the CS that the *CBS* is closed and *CBS* is normal

11.  $w \models V_{\sim CBS}^{CS}(w) = \text{false}$ ; CS does not know that *CBS* is not normal
12.  $RR = \text{true}$ ; *RR* is normal
13.  $w \models V_{RR}^{Relay}(w) = \text{true}$ ; *RR* is normal in relay world
14.  $IBT_{PLC,Relay}RR$ ; relay tells PLC that *RR* is normal and PLC believes it
15.  $w \models V_{RR}^{PLC}(w) = \text{true}$ ; *RR* is normal in PLC world
16.  $IBT_{CS,PLC}RR$ ; PLC tells CS that *RR* is normal and CS believes it
17.  $w \models V_{RR}^{CS}(w) = \text{true}$ ; *RR* is normal in CS world
18.  $Proj_{fR}(RR) = fR, \sim iCBOpenCheck \implies \sim CBS$ ; when the invariant *iCBOpenCheck* fails, CS deduces that *CBS* is not normal
19.  $w \models V_{\sim CBS}^{CS}(w) = \text{true}$ ; CS world now has deduced that *CBS* is abnormal
20.  $S'' = (S_{invariant}, S_{CBS})$ ; System is working normally if and only if  $S''$  is true
21.  $\sim MSDND(ES): \exists w \in W \vdash [(S'' \oplus S_{\sim CBS})] \wedge [w \models (\exists V_{\sim CBS}^{CBS}(w) \wedge \nexists V_{CBS}^{CS}(w))]$

When the CB is open, the *fR* should be zero; if *fR* is not zero, then that indicates that the *CBS* at the CS is not correct and it is actually closed. Hence the system is no longer MSDND secure. This is demonstrated in Figure 6.9. This theorem can be used to break twelve MSDND secure paths in the system out of the fifteen as shown in Table 6.4. The three CB Q1-1, Q1-2 and Q2 does not have a relay or a smart meter next to them to validate their state through this invariant.

**Note:** For the circuit breaker Q2A there are no relays next to it, we make use of the frequency reading from the AMI in the invariant *iCBOpenCheck* instead of *fR*. □

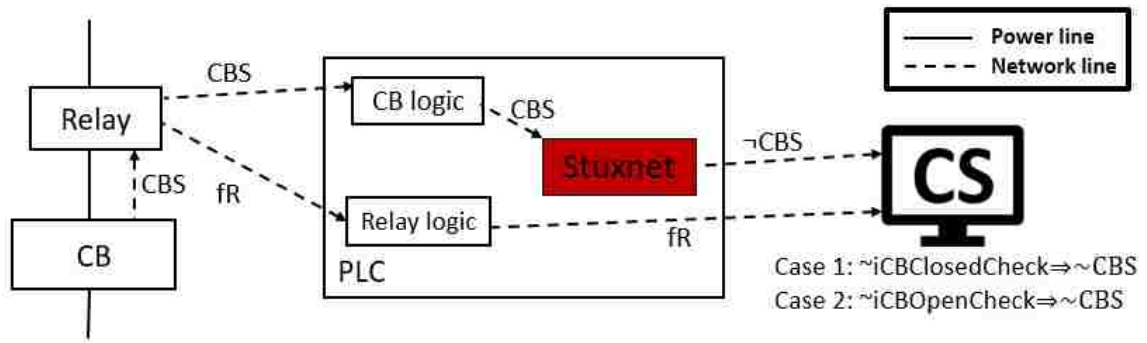


Figure 6.9. Information flow when *CBS* is abnormal but SCADA shows the inverse of it, and invariant is considered. Attack model for this is explained in Theorem 8, attack detection when *CB* is originally open is explained in Theorem 9, and attack detection when *CB* is originally closed is explained in Theorem 10.

*Analysis of vulnerability in CBS and RR information path.*

**Theorem 11.** *The Circuit breaker status CBS and the relay reading RR are MSDND secure at the CS when the CS commands the CB to open but CB is closed and also when the CS commands the CB to close but CB is open.*

*Proof.* Let *CBC* represent the command sent by the CS to the CB.

1.  $CBC = \text{true}$ ; *CBC* is normal
2.  $w \models V_{CBC}^{CS}(w) = \text{true}$ ; *CBC* is normal in CS world
3.  $IBT_{PLC,CS} CBC$ ; CS sends *CBC* to PLC and PLC believes it
4.  $w \models V_{CBC}^{PLC}(w) = \text{true}$ ; *CBC* is true in PLC world
5.  $IBT_{Stuxnet,PLC} CBC$ ; Stuxnet intercepts the normal *CBC* sent by PLC to relay
6.  $\sim CBC = \text{true}$ ; The Stuxnet reverses the *CBC*
7.  $w \models V_{\sim CBC}^{Stuxnet}(w) = \text{true}$ ; The Stuxnet knows that the *CBC* is not correct

8.  $IBT_{Relay,Stuxnet} CBC$ ; The Stuxnet reports the Relay that  $CBC$  is normal and Relay believes it
9.  $w \models V_{\sim CBC}^{Relay}(w) = \text{false}$ ; relay does not know that  $CBC$  is abnormal
10.  $IBT_{CB,Relay} CBC$ ; relay sends  $CBC$  to CB and CB believes it to be normal
11.  $w \models V_{\sim CBC}^{CB}(w) = \text{false}$ ; CB does not know that  $CBC$  is abnormal
12.  $\sim CBC \implies \sim CBS, \sim RR$ ; When the  $CBC$  is not normal then even the  $CBS$  and  $RR$  will not be normal
13.  $\sim CBS, \sim RR = \text{true}$ ;  $CBS$  and  $RR$  are not normal
14.  $w \models V_{\sim CBS, \sim RR}^{Relay}(w) = \text{true}$ ;  $CBS$  and  $RR$  are not normal in relay world
15.  $IBT_{Stuxnet,Relay} \sim CBS, \sim RR$ ; Stuxnet intercepts the abnormal  $CBS$  and  $RR$  sent by relay to PLC
16.  $w \models V_{\sim CBS, \sim RR}^{Stuxnet}(w) = \text{true}$ ; Stuxnet knows that  $CBS$  and  $RR$  are abnormal
17.  $IBT_{PLC,Stuxnet} CBS, RR$ ; The Stuxnet changes the  $CBS$  and  $RR$  values and tells the PLC that it is normal
18.  $w \models V_{\sim CBS, \sim RR}^{PLC}(w) = \text{false}$ ;  $CBS$  and  $RR$  are abnormal but in PLC world it appears normal
19.  $IBT_{CS,PLC} CBS, RR$ ; PLC tells CS that  $CBS$  and  $RR$  are normal and CS believes that
20.  $w \models V_{CBS,RR}^{CS}(w) = \text{true}$ ; In the CS world  $CBS$  and  $RR$  are true
21. MSDND(ES):  $\exists w \in W \vdash [(S_{CBS,RR} \oplus S_{\sim CBS,RR})] \wedge [w \models (\nexists V_{\sim CBS,RR}^{CS}(w) \wedge \nexists V_{CBS,RR}^{CS}(w))]$



The Stuxnet reverses the actual CB command  $CBC$  sent from the CS and then sends false positive  $RR$  and  $CBS$  to the CS. it is not possible to deduce at the CS whether the  $CBS$  and  $RR$  are correct or not. Thus, the system is MSDND secure. There are thirty such MSDND secure paths in the system, fifteen when the CS instructs open but CB is closed, and fifteen when the CS instructs closed but CB is open. There are two possible cases for each of the listed paths in Table 6.4.  $\square$

**Theorem 12.** *The Circuit breaker status  $CBS$  and the relay reading  $RR$  are not MSDND secure at the CS when the CS commands the CB to open but CB is closed if the invariants are considered.*

*Proof.* Let us assume that the frequency reading  $f$  from the AMI is correct. Let  $fR$  be the frequency reading in  $RR$  and let the invariant  $iCBRROpen : CBS == open \text{ and } f == 0$  and  $f == fR$  be the invariant in the CS.

1.  $CBC = true$ ;  $CBC$  is normal
2.  $w \models V_{CBC}^{CS}(w) = true$ ;  $CBC$  is normal in CS world
3.  $IBT_{PLC,CS} CBC$ ; CS sends  $CBC$  to PLC and PLC believes it
4.  $w \models V_{CBC}^{PLC}(w) = true$ ;  $CBC$  is true in PLC world
5.  $IBT_{Stuxnet,PLC} CBC$ ; Stuxnet intercepts the normal  $CBC$  sent by PLC to relay
6.  $\sim CBC = true$ ; The Stuxnet reverses the  $CBC$
7.  $w \models V_{\sim CBC}^{Stuxnet}(w) = true$ ; The Stuxnet knows that the  $CBC$  is not correct
8.  $IBT_{Relay,Stuxnet} CBC$ ; The Stuxnet reports the Relay that  $CBC$  is normal and Relay believes it
9.  $w \models V_{\sim CBC}^{Relay}(w) = false$ ; relay does not know that  $CBC$  is abnormal

10.  $IBT_{CB,Relay} CBC$ ; relay sends  $CBC$  to CB and CB believes it to be normal, here  $CBC=open$
11.  $w \models V_{\sim CBC}^{CB} (w) = false$ ; CB does not know that  $CBC$  is abnormal
12.  $\sim CBC \implies \sim CBS, \sim RR$ ; When the  $CBC$  is not normal then even the  $CBS$  and  $RR$  will not be normal
13.  $\sim CBS, \sim RR = true$ ;  $CBS$  and  $RR$  are not normal
14.  $w \models V_{\sim CBS, \sim RR}^{Relay} (w) = true$ ;  $CBS$  and  $RR$  are not normal in relay world
15.  $IBT_{Stuxnet,Relay} \sim CBS, \sim RR$ ; Stuxnet intercepts the abnormal  $CBS$  and  $RR$  sent by relay to PLC
16.  $w \models V_{\sim CBS, \sim RR}^{Stuxnet} (w) = true$ ; Stuxnet knows that  $CBS$  and  $RR$  are abnormal
17.  $IBT_{PLC,Stuxnet} CBS, RR$ ; The Stuxnet changes the  $CBS$  and  $RR$  values and tells the PLC that it is normal
18.  $w \models V_{\sim CBS, \sim RR}^{PLC} (w) = false$ ;  $CBS$  and  $RR$  are abnormal but in PLC world it appears normal
19.  $IBT_{CS,PLC} CBS, RR$ ; PLC tells CS that  $CBS$  and  $RR$  are normal and CS believes that
20.  $w \models V_{CBS,RR}^{CS} (w) = true$ ; In the CS world  $CBS$  and  $RR$  are true
21.  $\sim CBS \implies \sim f$ ; as  $CBS$  is not normal, the AMI readings are also not normal
22.  $IBT_{CS,AMI} \sim f$ ; We obtain the frequency reading from the AMI at the CS
23.  $w \models V_{\sim f}^{CS} (w) = true$ ;  $f$  is not normal in CS world
24.  $Proj_{fR}(RR)=fR$ ;
25.  $\sim iCBRROpen \implies \sim CBS, \sim RR$ ; when the invariant  $iCBRROpen$  fails, CS deduces that  $CBS$  and  $RR$  are not normal

26.  $w \models V_{\sim CBS, \sim RR}^{CS}(w) = \text{true}$ ; CS world now has deduced that *CBS* and *RR* are not normal
27.  $S'' = (S_{iCBRROpen}, S_{CBS,RR})$ ; System is working normally if and only if  $S''$  is true
28.  $\sim \text{MSDND}(\text{ES}): \exists w \in W \vdash [(S'' \oplus S_{\sim CBS,RR})] \wedge [w \models (\exists V_{\sim CBS,RR}^{CS}(w) \wedge \nexists V_{CBS,RR}^{CS}(w))]$

If the CB is open, then  $f$  should be zero; if the *RR* is true, then it should match with the corresponding AMI reading. When this is not true, we can deduce that the *RR* and the *CBS* at the CS are incorrect as shown in Figure 6.10. This invariant can be used to break eleven out of the fifteen MSDND secure paths. The four circuit breakers Q1-1, Q1-2, Q2 and Q2A does not have a relay next to them to validate their state through the invariant  $iCBRROpen$ . The paths that are broken in Table 6.4 holds, but the line item 6 involving Q2A does not have an invariant.  $\square$

**Theorem 13.** *The Circuit breaker status CBS and the relay reading RR are not MSDND secure at the CS when the CS commands the CB to close but CB is open if the invariants are considered.*

*Proof.* Let us assume that the frequency reading  $f$  from the AMI is correct. Let  $fR$  be the frequency reading in *RR* and let the invariant  $iCBRRClose : CBS == \text{closed and } f \neq 0$  and  $f == fR$  be the invariant in the CS.

1.  $CBC = \text{true}$ ; *CBC* is normal
2.  $w \models V_{CBC}^{CS}(w) = \text{true}$ ; *CBC* is normal in CS world
3.  $IBT_{PLC,CS} CBC$ ; CS sends *CBC* to PLC and PLC believes it
4.  $w \models V_{CBC}^{PLC}(w) = \text{true}$ ; *CBC* is true in PLC world
5.  $IBT_{Stuxnet,PLC} CBC$ ; Stuxnet intercepts the normal *CBC* sent by PLC to relay

6.  $\sim CBC = \text{true}$ ; The Stuxnet reverses the  $CBC$
7.  $w \models V_{\sim CBC}^{Stuxnet}(w) = \text{true}$ ; The Stuxnet knows that the  $CBC$  is not correct
8.  $IBT_{Relay,Stuxnet} CBC$ ; The Stuxnet reports the Relay that  $CBC$  is normal and Relay believes it
9.  $w \models V_{\sim CBC}^{Relay}(w) = \text{false}$ ; relay does not know that  $CBC$  is abnormal
10.  $IBT_{CB,Relay} CBC$ ; relay sends  $CBC$  to CB and CB believes it to be normal, here  $CBC = \text{open}$
11.  $w \models V_{\sim CBC}^{CB}(w) = \text{false}$ ; CB does not know that  $CBC$  is abnormal
12.  $\sim CBC \implies \sim CBS, \sim RR$ ; When the  $CBC$  is not normal then even the  $CBS$  and  $RR$  will not be normal
13.  $\sim CBS, \sim RR = \text{true}$ ;  $CBS$  and  $RR$  are not normal
14.  $w \models V_{\sim CBS, \sim RR}^{Relay}(w) = \text{true}$ ;  $CBS$  and  $RR$  are not normal in relay world
15.  $IBT_{Stuxnet,Relay} \sim CBS, \sim RR$ ; Stuxnet intercepts the abnormal  $CBS$  and  $RR$  sent by relay to PLC
16.  $w \models V_{\sim CBS, \sim RR}^{Stuxnet}(w) = \text{true}$ ; Stuxnet knows that  $CBS$  and  $RR$  are abnormal
17.  $IBT_{PLC,Stuxnet} CBS, RR$ ; The Stuxnet changes the  $CBS$  and  $RR$  values and tells the PLC that it is normal
18.  $w \models V_{\sim CBS, \sim RR}^{PLC}(w) = \text{false}$ ;  $CBS$  and  $RR$  are abnormal but in PLC world it appears normal
19.  $IBT_{CS,PLC} CBS, RR$ ; PLC tells CS that  $CBS$  and  $RR$  are normal and CS believes that
20.  $w \models V_{CBS, RR}^{CS}(w) = \text{true}$ ; In the CS world  $CBS$  and  $RR$  are true

21.  $\sim CBS \implies \sim f$ ; as  $CBS$  is not normal, the AMI readings are also not normal
22.  $IBT_{CS,AMI} \sim f$ ; We obtain the frequency reading from the AMI at the CS
23.  $w \models V_{\sim f}^{CS}(w) = \text{true}$ ;  $f$  is not normal in CS world
24.  $Proj_{fR}(RR) = fR$ ;
25.  $\sim iCBRRClose \implies \sim CBS, \sim RR$ ; when the invariant  $iCBRRClose$  fails, CS deduces that  $CBS$  and  $RR$  are not normal
26.  $w \models V_{\sim CBS,RR}^{CS}(w) = \text{true}$ ; CS world now has deduced that  $CBS$  and  $RR$  are abnormal
27.  $S'' = (S_{iCBRRClose}, S_{CBS,RR})$ ; System is working normally if and only if  $S''$  is true
28.  $\sim MSDND(ES): \exists w \in W \vdash [(S'' \oplus S_{\sim CBS,RR})] \wedge [w \models (\exists V_{\sim CBS,RR}^{CS}(w) \wedge \nexists V_{CBS,RR}^{CS}(w))]$

If the CB is closed, then  $f$  should not be zero; if the  $RR$  is true, then it should match with the corresponding AMI reading. When this is not true, we can deduce that the  $RR$  and the  $CBS$  at the CS are incorrect as shown in Figure 6.10. This invariant can be used to break eleven out of the fifteen MSDND secure paths. The four circuit breakers Q1-1, Q1-2, Q2 and Q2A does not have a relay next to them to validate their state through the invariant  $iCBRRClose$ . The paths that are broken in Table 6.4 holds, but the line item 6 involving Q2A does not have an invariant.  $\square$

- **Multi-point attacks**

*Analysis of vulnerability in RPM and RR information path.*

**Theorem 14.** *The RPM reading  $RPM$  from VSD and the relay readings  $RR$  from the relay are MSDND secure at the Control System (CS) when  $RPM$  and  $RR$  are not normal but the readings are normal.*

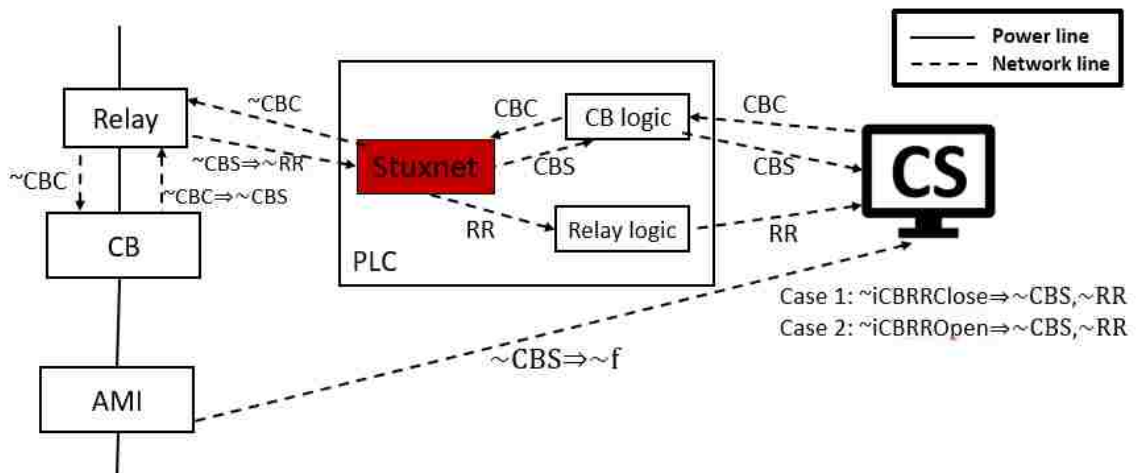


Figure 6.10. Information flow when  $CBS$  and  $RR$  are abnormal, and invariant is considered. Attack model for this is explained in Theorem 11, attack detection when  $CB$  is originally closed is explained in Theorem 12, and attack detection when  $CB$  is originally open is explained in Theorem 13.

*Proof.* Here the  $RPM$  reading from VSD and the relay readings (current, voltage, frequency)  $RR$  from the relay are incorrect at the CS. This is a multi-point attack and there are two Stuxnets involved. One executes at the MPLC and corrupts the  $RR$  sent to the CS, the other executes at the SPLC and corrupts the  $RPM$  reading sent to the CS.

1.  $\sim RPM = \text{true}$ ; The  $RPM$  is not normal
2.  $w \models V_{\sim RPM}^{VSD}(w) = \text{true}$ ;  $RPM$  is not normal in VSD world
3.  $IBT_{Stuxnet, VSD} \sim RPM$ ; Stuxnet intercepts the abnormal  $RPM$  sent by VSD to SPLC
4.  $w \models V_{\sim RPM}^{Stuxnet}(w) = \text{true}$ ; Stuxnet observes that  $RPM$  is abnormal
5.  $IBT_{SPLC, Stuxnet} RPM$ ; Stuxnet modifies  $RPM$  to make it look normal and transmits it to SPLC and SPLC believes it
6.  $w \models V_{RPM}^{SPLC}(w) = \text{true}$ ;  $RPM$  looks normal in SPLC world
7.  $IBT_{CPLC, SPLC} RPM$ ; SPLC tells CPLC that  $RPM$  is normal and CPLC believes it

8.  $w \models V_{RPM}^{CPLC}(w) = \text{true}$ ;  $RPM$  looks normal in CPLC world
9.  $IBT_{CS,CPLC} RPM$ ; CPLC tells CS that  $RPM$  is normal and CS believes it
10.  $w \models V_{RPM}^{CS}(w) = \text{true}$ ; CS believes that  $RPM$  is normal
11.  $\sim RR = \text{true}$ ;  $RPM$  is not normal so the  $RR$  is also not normal
12.  $w \models V_{\sim RR}^{Relay}(w) = \text{true}$ ;  $RR$  is not normal in relay world
13.  $IBT_{Stuxnet,Relay} \sim RR$ ; Stuxnet intercepts the abnormal  $RR$  sent by relay to MPLC
14.  $w \models V_{\sim RR}^{Stuxnet}(w) = \text{true}$ ; Stuxnet observes that  $RR$  is abnormal
15.  $IBT_{MPLC,Stuxnet} RR$ ; Stuxnet modifies  $RR$  to make it look normal and transmits it to MPLC and MPLC believes it
16.  $w \models V_{RR}^{MPLC}(w) = \text{true}$ ;  $RR$  appears normal in MPLC world
17.  $IBT_{CPLC,MPLC} RR$ ; MPLC tells CPLC that  $RR$  is normal and CPLC believes it
18.  $w \models V_{RR}^{CPLC}(w) = \text{true}$ ;  $RR$  is normal in  $CPLC$  world
19.  $IBT_{CS,CPLC} RR$ ; CPLC tells CS that  $RR$  is normal and CS believes it
20.  $w \models V_{RR}^{CS}(w) = \text{true}$ ; CS observes  $RR$  to be normal
21.  $S = (S_{RPM}, S_{RR})$ ;  $S$  is a world where  $RR$  and  $RPM$  are normal
22.  $S'' = (S_{\sim RPM}, S_{\sim RR})$ ;  $S''$  is a world where  $RR$  and  $RPM$  are abnormal
23. MSDND(ES):  $\exists w \in W \vdash [(S \oplus S'')] \wedge [w \models (\nexists V_{\sim RPM}^{CS}(w) \wedge \nexists V_{RPM}^{CS}(w) \wedge \nexists V_{\sim RR}^{CS}(w) \wedge \nexists V_{RR}^{CS}(w))]$

The CS believes the false  $RPM$  reading reported by the Stuxnet and the false positive  $RR$  reading reported by the other Stuxnet. Therefore,  $RPM$  information and  $RR$  are MSDND secure at the CS. There are three such MSDND secure paths in the system as shown in Table 6.5. □

Table 6.5. Summary of MSDND analysis for RPM and RR information path

S.No.	MSDND Secure Paths	Invariant Available
1	VSD1→SPLC→CPLC→CS and MIED2→MPLC→CPLC→CS	Yes
2	VSD2→SPLC→CPLC→CS and MIED1→MPLC→CPLC→CS	Yes
3	VSD3→SPLC→CPLC→CS and GIED2→GPLC→CPLC→CS	Yes

**Theorem 15.** *The RPM reading RPM from VSD and the Relay Reading RR from the relay are not MSDND secure at the Control System (CS) when RPM and RR are not normal but the readings at CS are normal when the invariants are considered.*

*Proof.* Let us assume the frequency reading  $f$  from the AMI is correct. Let  $fR$  be the frequency reading from the relay. Let the invariant  $iRPM: RPM = 30f$  and  $iF: f == fR$  be in the control system.

1.  $\sim RPM = \text{true}$ ; The  $RPM$  is not normal
2.  $w \models V_{\sim RPM}^{VSD}(w) = \text{true}$ ;  $RPM$  is not normal in VSD world
3.  $IBT_{Stuxnet, VSD} \sim RPM$ ; Stuxnet intercepts the abnormal  $RPM$  sent by VSD to SPLC
4.  $w \models V_{\sim RPM}^{Stuxnet}(w) = \text{true}$ ; Stuxnet observes that  $RPM$  is abnormal
5.  $IBT_{SPLC, Stuxnet} RPM$ ; Stuxnet modifies  $RPM$  to make it look normal and transmits it to SPLC and SPLC believes it
6.  $w \models V_{RPM}^{SPLC}(w) = \text{true}$ ;  $RPM$  looks normal in SPLC world
7.  $IBT_{CPLC, SPLC} RPM$ ; SPLC tells CPLC that  $RPM$  is normal and CPLC believes it
8.  $w \models V_{RPM}^{CPLC}(w) = \text{true}$ ;  $RPM$  looks normal in CPLC world



9.  $IBT_{CS,CPLC} RPM$ ; CPLC tells CS that  $RPM$  is normal and CS believes it
10.  $w \models V_{RPM}^{CS}(w) = \text{true}$ ; CS believes that  $RPM$  is normal
11.  $\sim RR = \text{true}$ ; As  $RPM$  is not normal in the VSD world, it affects the  $RR$  in the link below it and hence  $RR$  is not normal
12.  $w \models V_{\sim RR}^{Relay}(w) = \text{true}$ ;  $RR$  is not normal in relay world
13.  $IBT_{Stuxnet,Relay} \sim RR$ ; Stuxnet intercepts the abnormal  $RR$  sent by relay to MPLC
14.  $w \models V_{\sim RR}^{Stuxnet}(w) = \text{true}$ ; Stuxnet observes that  $RR$  is abnormal
15.  $IBT_{MPLC,Stuxnet} RR$ ; Stuxnet modifies  $RR$  to make it look normal and transmits it to MPLC and MPLC believes it
16.  $w \models V_{RR}^{MPLC}(w) = \text{true}$ ;  $RR$  appears normal in MPLC world
17.  $IBT_{CPLC,MPLC} RR$ ; MPLC tells CPLC that  $RR$  is normal and CPLC believes it
18.  $w \models V_{RR}^{CPLC}(w) = \text{true}$ ;  $RR$  is normal in  $CPLC$  world
19.  $IBT_{CS,CPLC} RR$ ; CPLC tells CS that  $RR$  is normal and CS believes it
20.  $w \models V_{RR}^{CS}(w) = \text{true}$ ; CS observes  $RR$  to be normal
21.  $S = (S_{RPM}, S_{RR})$ ;  $S$  is a world where  $RR$  and  $RPM$  are normal
22.  $S'' = (S_{\sim RPM}, S_{\sim RR})$ ;  $S''$  is a world where  $RR$  and  $RPM$  are abnormal
23.  $\sim RPM \implies \sim f$ ; as  $RPM$  is not normal, the AMI readings are also not normal
24.  $IBT_{CS,AMI} \sim f$ ; CS obtains the  $f$  reading from smart meter and believes it
25.  $\sim iRPM \implies \sim RPM$ ; from the assumption that the frequency reading  $f$  from the AMI is correct and the invariant  $iRPM$ , the CS deduces that  $RPM$  is not normal

26.  $w \models V_{\sim RPM}^{CS}(w) = \text{true}$ ; CS now has deduced that  $RPM$  is abnormal
27. From (2.1),  $Proj_{fR}(RR) = fR, \sim iF \implies \sim RR$ ; from the assumption that the frequency reading  $f$  from the AMI is correct and the invariant  $iF$ , the CS finds that  $RR$  is abnormal
28.  $w \models V_{\sim RR}^{CS}(w) = \text{true}$ ; CS now has valuation function to know that  $RR$  is not normal
29.  $S_{invariant} = (S_{iRPM}, S_{iF})$ ; Defining a world with invariants
30.  $S^1 = (S_{invariant}, S)$ ; System is working normally if and if only  $S^1$  is true
31.  $\sim \text{MSDND}(\text{ES}): \exists w \in W \vdash [(S^1 \oplus S'')] \wedge [w \models (\exists V_{\sim RPM}^{CS}(w) \wedge \nexists V_{RPM}^{CS}(w) \wedge \exists V_{\sim RR}^{CS}(w) \wedge \nexists V_{RR}^{CS}(w))]$

The system is not MSDND secure as we have a valuation function for abnormal working of the system and hence fault/threat can be detected as shown in Figure 6.11. This proof can be applied to break all the three MSDND secure paths listed in Table 6.5.  $\square$

## 6.2. DATA-CENTRIC APPROACH

**6.2.1. Data.** The data collected from the EPIC testbed over a period of two weeks is used to carry out the analyses. Data is extracted from a SCADA system using the Historian. The SCADA system contains the readings from eleven relays that have voltage, current, frequency and power readings as shown in Figure 6.12. Other readings, for example, the circuit breaker statuses and status about the three motors like the flags set, rotation per minute, and statuses, are also included in the SCADA system. In total, there are around two hundred and ninety different variables from the SCADA system, and the sampling rate for collecting the data is ten seconds.

There are two different types of data in the EPIC dataset:

1. Numeric data- frequency, voltage, current, power, rpm
2. Binary data- circuit breaker on/off status, trip status, relay on/off state

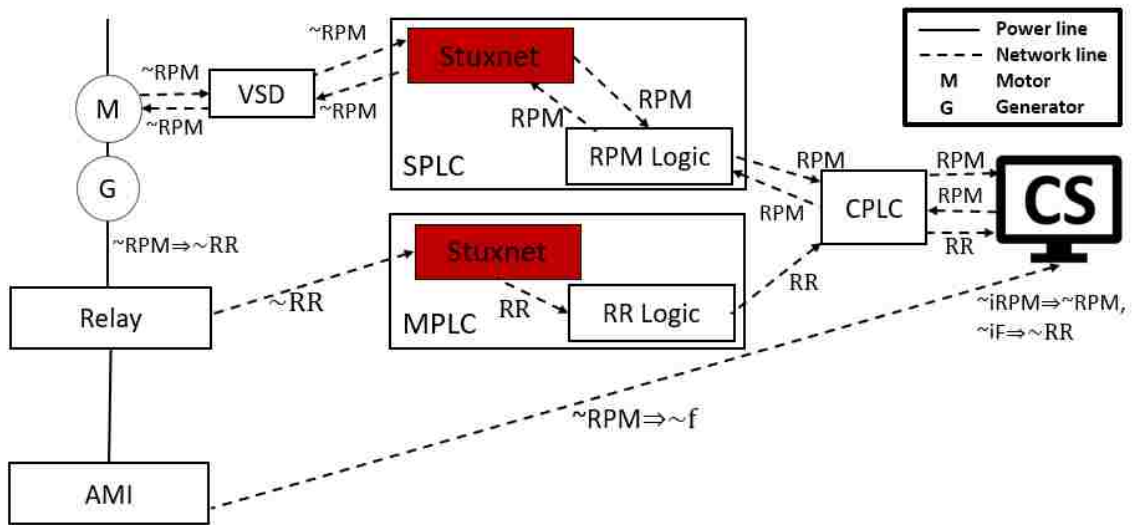


Figure 6.11. Information flow when  $RPM$  and  $RR$  are actually abnormal and invariant is considered. Attack model for this is explained in Theorem 14. Attack detection is explained in Theorem 15.

**6.2.2. Invariant Generation using Linear Regression.** Figure 6.13 shows the variation of the fourteen variables of the relay GIED1 over a six-hour period. From this figure, it is understood that certain variables vary relative to one and another and there exists a strong linear relationship between certain variables. Throughout a power grid, several variables are linearly related to each other, which is why linear regression would be a suitable approach for generating invariants.

The binary data and the smart meter readings from the AMI were removed from the processed dataset, because binary data like the breaker status would not make a valid field for the linear regression algorithm. Linear regression was applied to the remaining one hundred and fifty-two numeric data values of EPIC to derive mathematical relations between them. The very high coefficient of determination ( $R^2$ ) of the prediction was set for deriving invariants using linear regression for a higher accuracy. An  $R^2$  score of .99 out of



Figure 6.12. Reading from the Relay GIED1

1 was set for deriving invariants. The algorithm would then run through each column and determine the mathematical relation of the form  $A = x \times B$ , where  $A$  and  $B$  are column names and  $x$  is a constant.

Care was taken to avoid duplicate invariants by considering only the upper triangular matrix of the data frame while generating invariants. The fields  $A$  and  $B$  were rearranged in such a way while generating invariants that  $x$  was greater than 1. This was done to avoid generating the invariant  $\frac{A1}{B1} = 2$  and  $\frac{B1}{A1} = 0.5$  differently, which would make the grouping of invariants tedious. Filtering was done to remove the invariant relation between different devices like frequency of relay1 with voltage of relay2 because one of them can be closed and the other can be in open state and that time the relation might still hold just because one of them is zero, which would not actually make sense. For an  $R^2$  score of .99, a total of 215 invariants were generated and 199 of them were categorized into nine types based on electrical equations that obey the law of physics. The nine types of invariants are as follows:

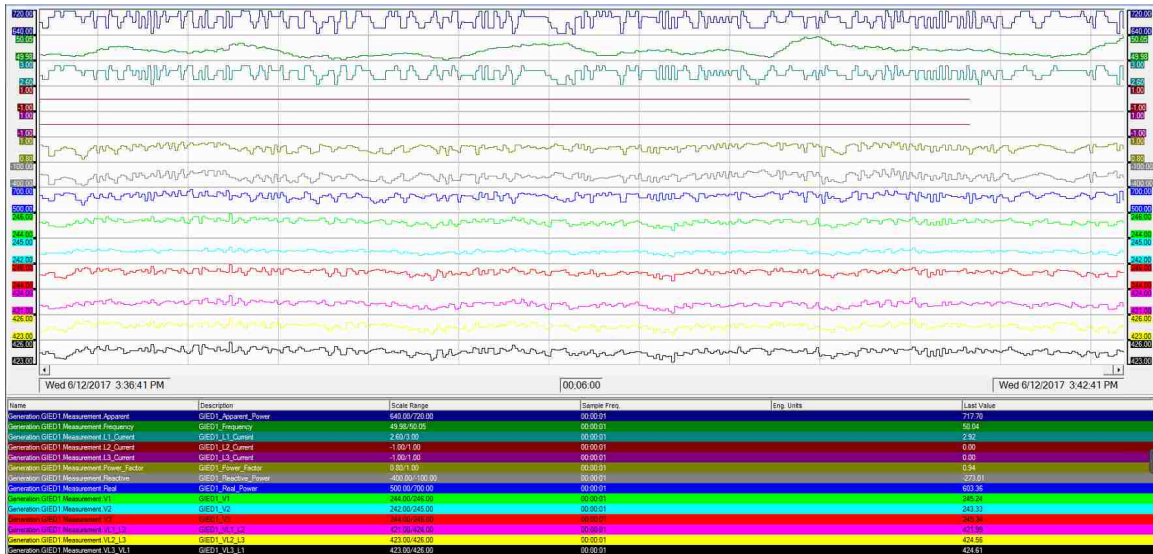


Figure 6.13. Variation of the Relay GIED1 Variables over Six Hours

**Type 1.** The Type 1 invariant is based on the power triangle shown in Figure 6.14.

Nine invariants were generated, and they were of the following format:

$$x = \text{Sec}\theta = A/B = \frac{\text{Apparent power}}{\text{Real power}}$$

From these nine invariants, it was found that the impedance angle  $\theta$  of the EPIC system was around  $-12^\circ$ . A sample invariant from this type is of the form:

$$\frac{\text{SIED2.Measurement.Apparent}}{\text{SIED2.Measurement.Active}} = 1.000016576$$

**Type 2.** The Type 2 invariant is based on the electrical relation between line to line voltage ( $V_{LL}$ ) and line to neutral voltage ( $V_{LN}$ ) in a three-phase AC circuit, which is given by the equation:

$$V_{LL} = \sqrt{3} \times V_{LN}$$

There is a total of eighty-one invariants of this form, and a sample invariant from this stage is of the form:

$$\text{TIED2.Measurement.VL3_VL1} = 1.732599711 \times \text{TIED2.Measurement.V1}$$

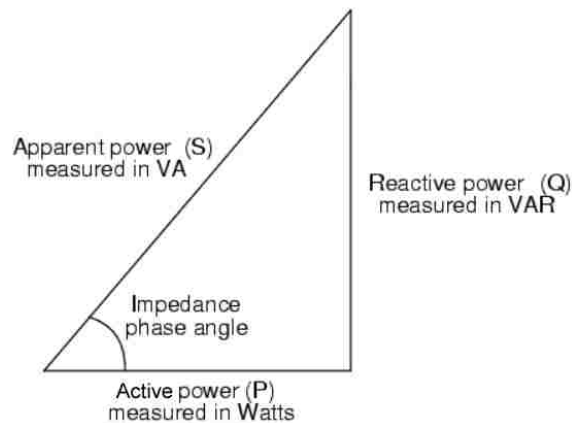


Figure 6.14. The Power Triangle Relating Apparent Power to Active (Real) Power and Reactive Power

**Type 3.** The Type 3 invariant is based on the relation between the *RPM* and the line to line voltage ( $V_{LL}$ ). There is no generic equation in physics available for this relation, but for EPIC it is defined by the equation:

$$RPM = k \times V_{LL}$$

where  $k$  is a constant and is different for different circuits. Nine invariants were generated in this type, and here is a sample invariant:

$$VSD1.ActualSpeed = 3.545424313 \times MIED2.Measurement.VL2\_L3$$

**Type 4.** The Type 4 invariant defines a relation between the frequency and the line to neutral voltage. There is no formally defined equation available for this relation, but a large number of invariants (twenty-four) were generated for the EPIC system with a more or less same constant, which validates this invariant with respect to this system. The average constant was found to be 4.85. The invariant in this type would appear as follows:

$$TIED2.Measurement.V1 = 4.76740974 \times TIED2.Measurement.Frequency$$

**Type 5.** The Type 5 invariant is similar to the Type 3 invariant and is a relation between the *RPM* and the line to neutral voltage ( $V_{LN}$ ). It also satisfies the equation specified in the Type 2 invariant. The  $k$  value in this relation is  $\sqrt{3}$  times the  $k$  value in Type 3. Just like Type 3, nine invariants are generated for this type. Below is a sample invariant:

$$VSD2.ActualSpeed = 6.182578696 \times MIED1.Measurement.V2$$

**Type 6.** The Type 6 invariant is similar to the Type 4 invariant and is a relation between the frequency and the line to line voltage ( $V_{LN}$ ). This obeys the Type 2 relation; the  $k$  value in this relation is  $\sqrt{3}$  times the  $k$  value in Type 4, and the average  $k$  value is 8.401. There are twenty-four invariants generated in this type and an invariant of this type would appear as follows:

$$TIED4.Measurement.VL2\_L3 = 8.464169799 \times TIED4.Measurement.Frequency$$

**Type 7.** The Type 7 invariant is based on a defined electrical relation between the *RPM* and the frequency. As per law of physics, the *RPM* of the system is given by:

$$RPM = \frac{120 \times F}{P}$$

Here  $F$  is the frequency and  $P$  is the number of poles in the motor. The motor used in the EPIC system has 4 poles, so this makes the above equation as follows:

$$RPM = 30 \times F$$

Three invariants were generated, one for each motor, and they were found to accurately match the above equation. Below is a sample invariant of this type:

$$VSD3.ActualSpeed = 30 \times GIED2.Measurement.Frequency$$

**Type 8 and Type 9.** The Type 8 and 9 invariants are based on the similarity between the impedance and the resistance in the EPIC system. The Active power is given by:

$$ActivePower = I^2 \times R$$

Here  $I$  is the current and  $R$  is the resistance. The apparent power is given by:

$$\text{Apparent Power} = I^2 \times Z$$

Here  $Z$  is the magnitude of the impedance of the system. There are forty invariants generated for Type 8 and 9.

The sample invariants of Type 8 and 9 are of the form:

$$\frac{SIED2.Measurement.Real}{SIED2.Measurement.L3\_Current} = 722.1180407$$

$$\frac{SIED2.Measurement.Apparent}{SIED2.Measurement.L3\_Current} = 722.1486546$$



## 7. RESULTS

### 7.1. DESIGN-CENTRIC APPROACH

More than one hundred information paths were analyzed in the EPIC testbed, and eighty-nine information paths were found to be MSDND secure. Whenever an information path is MSDND secure it is bad for the system because the operator will not have any valuation function to identify that the system is in a corrupt state. The fewer the MSDND secure paths, the better it is for the system. Invariants were used to break as many as seventy-three MSDND secure paths in the system. Out of these, twenty-four invariants described in Theorem 11 and 12 were implemented in the system. Man-in-the-middle attacks were simulated in the corresponding information paths by corrupting the values in the PLC being sent to SCADA. Invariants involving smart meter readings were not implemented because at present the smart meters in the EPIC are daisy chained to a single Raspberry Pi and hence the readings are not accurate. The results of the study is summarized in the Table 7.1.

The circuit breaker status flows from the circuit breaker to the Historian in the path as shown in Figure 7.1. The invariants from Theorem 11 and 12 were tested against the EPIC data collected through the Historian software. On analysis, it was found that the status of circuit breaker going to the OPC server was actually correct, but it gets corrupted in the OPC server to the Historian path. This was because when invariants were implemented directly on the OPC server, the CBS was satisfying the invariants, but when it was implemented on data collected through Historian, CBS did not satisfy the invariants.

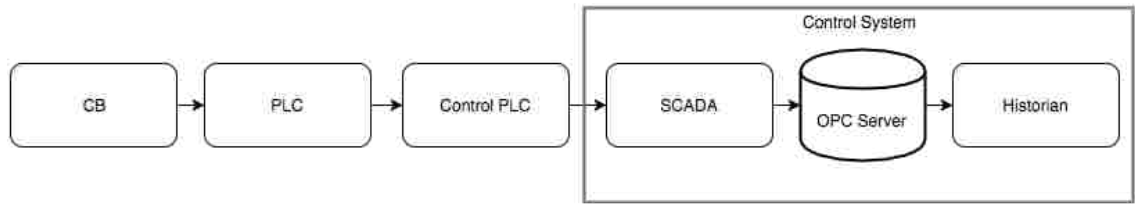


Figure 7.1. CBS flow from the circuit breaker to Historian

Table 7.1. Result summary of MSDND analysis

Summary	Count
Information paths analyzed	100+
MSDND secure paths found	89
MSDND secure paths broken using invariants (total invariants generated)	73
Invariants implemented in the system	24

## 7.2. DATA-CENTRIC APPROACH

With the training dataset from the EPIC system, we get candidate invariants between system variables by applying linear regression. A code to automate the generation of a Python script to implement the invariant logic is created using the generated linear regression invariants as inputs. Given a set of invariants, the success of these results is evaluated by testing their performance on the EPIC system. The testing dataset is the set of execution logs of the system gathered across multiple months. Thanks to the large sampling size, the data can accommodate bias caused by different insulations. To ensure a high representativeness, only data during maximum operation of the EPIC system is considered.

To gain a better understanding of the large set of invariants, each invariant is classified into a type using a mathematical relation. It ends up with nine distinct types over a total of one hundred and ninety-nine valid invariants. After classification, each type of invariant is evaluated by sampling and finding the mean.

In real-time systems, the power variables will not strictly follow the invariant equations: there will be slight deviation from the actual relation. If the deviation value is less, then the invariant is better. If an invariant with a higher deviation percentage is implemented in the system, then it will raise false alarms. Consider an invariant relation involving two variables  $P$  and  $Q$  given by the relation:

$$P = k \times Q$$

where  $k$  is a constant. Then, the relation involving deviation percentage and invariant is given by the following equation:

$$\left( \frac{100 - \text{deviation percentage}}{100} \times P \right) \leq (k \times Q) \leq \left( \frac{100 + \text{deviation percentage}}{100} \times P \right)$$

The success rate of each invariant type is calculated for deviation percentages  $\pm 1\%$  to  $\pm 6\%$ . The success rate of an invariant for a particular deviation percentage is given by the following relation:

$$\text{Success rate} = \frac{\text{Number of true alarms raised in an interval}}{\text{Total number of alarms raised in an interval}} \times 100 \%$$

From Figures 7.2 and 7.3, all nine types of invariants experience monotonic increases on the success percentage as the deviation goes up. In another words, when releasing the restriction on the percentage of deviation, more linear regression generated invariants tend to be accepted by the power grid system. Type 1 to 8 all achieve a success rate high than 98.5%. However, the success rate given by Type 9 is among the 30s.

### 7.3. COMPARISON BETWEEN DeC AND DaC GENERATED INVARIANTS

The DeC invariants are generated by making use of SCADA and AMI variables, but the DaC invariants are generated only using the SCADA variables, because of the issue mentioned in Section 7.1. In the nine Stuxnet attacks that were modeled, the DeC invariants can identify eight of them, as seen in the proofs. The DaC invariants generated without AMI variables cannot identify any of the attacks, but if AMI variables are considered, then

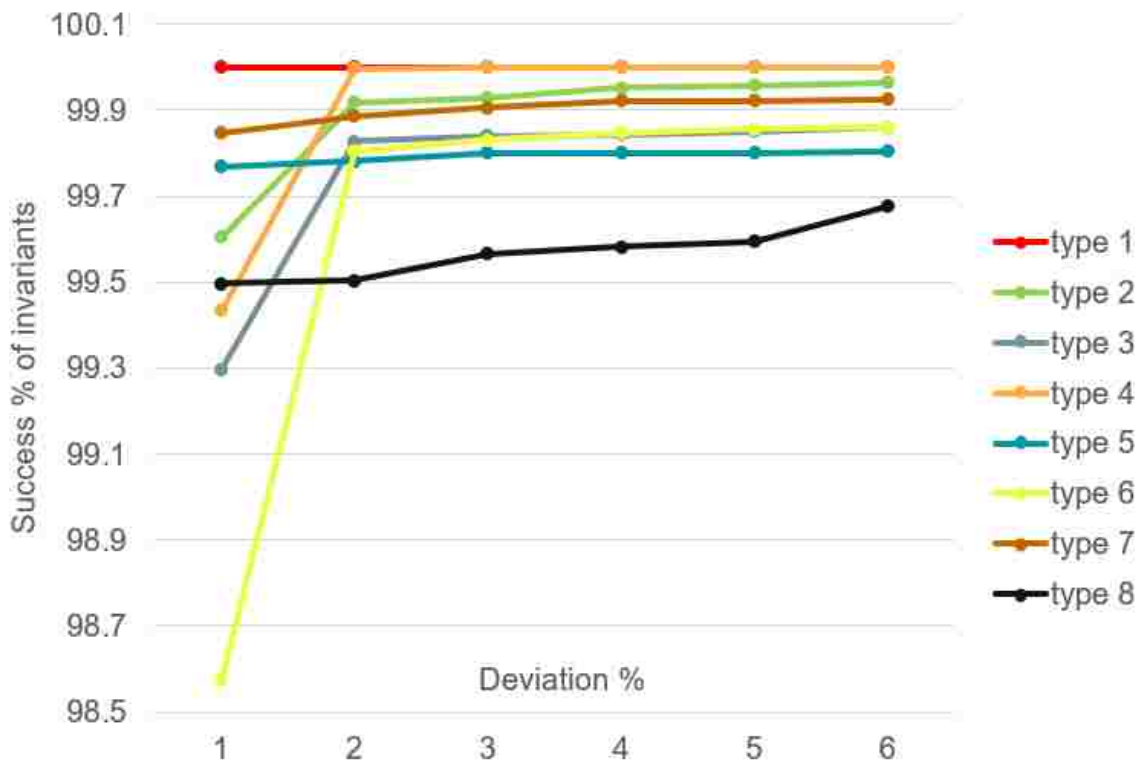


Figure 7.2. Success rates of the invariants of type 1 to 8

it can identify one attack among the nine. This is because in DeC, there is a conjunction present between two conditions, and we also consider Boolean states in this approach, which makes it easier to identify the information path in which the fault/attack occurred. However, because of the variety of system properties that were captured in DaC, these invariants are much better in identifying faults that occur in the SCADA system when it is working normally, and also in identifying uncorrelated attacks. For example, if an attacker changes the line to line voltage of a particular relay, but did not change the line to neutral voltage, the Type 2 DaC invariant would raise an alarm. A DeC invariant that uses both binary (status) and numeric data is much better at identifying correlated attacks where the attacker manages to corrupt all related variables with respect to a particular device. The comparison between DeC and DaC generated invariants are summarized in the Table 7.2.

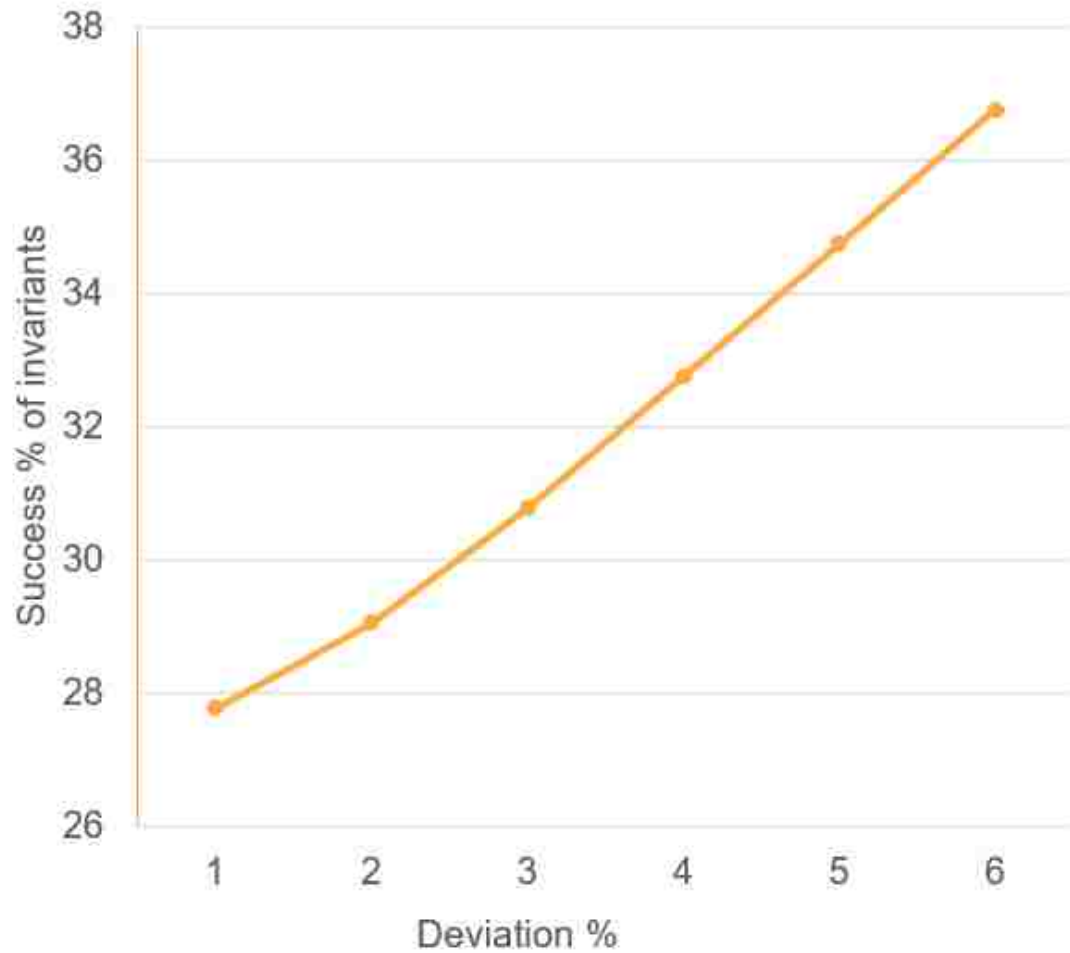


Figure 7.3. Success rate of the type 9 invariant

Table 7.2. Summary of DeC and DaC generated invariants

<b>Summary</b>	<b>Count</b>
Stuxnet attacks modeled	9
DeC invariants generated	73
DaC invariants generated (without AMI variables)	199
Attacks DeC invariants identify	8
Attacks DaC invariants (without AMI variables) identify	0
Attacks DaC invariants could identify (with AMI variables)	1

## 8. CONCLUSION

Vulnerable information paths were found in the EPIC testbed by MSDND analysis. Over seventy-three invariants were created manually using the physics of the system. Some of these invariants were implemented on the live system. Man-in-the-middle attacks were launched, and on all instances they identified the attack and broke the MSDND secure path, which is good for the system. Some invariants were also run on the data collected from EPIC, which helped identify the problem in the logger of the EPIC system.

Over one hundred and fifty-two numeric variables in the SCADA system of the EPIC testbed were analyzed using linear regression, and one hundred and ninety-nine invariants were generated. Scripts were created to automate the generation of scripts to implement the created invariants. The invariants were then categorized into nine types based on the defined electrical equations and the efficiency of each type was analyzed for various deviation percentages ranging from  $\pm 1\%$  to  $\pm 6\%$ , which is the allowed deviation in the EPIC system.

The invariants generated through DeC and DaC approaches were compared for their efficiency in identifying fault/attack, and it was found that the DeC invariants are better in identifying correlated attacks and DaC invariants work better in identifying faults and uncorrelated attacks in the system. DeC invariant generation heavily relies on the knowledge of the system, and generating invariants for a large smart grid could be time-consuming. To build a highly secure system, DeC would be the best approach to generate invariants although it consumes more time. To identify faults arising in the system due to day-to-day operation, DaC would be the best approach to generate invariants.

## 9. FUTURE WORK

The circuit breaker status was incorrect in the EPIC data that was collected by Historian. To resolve this, a logger software can be created that directly retrieves live values of the circuit breaker data from the OPC server and logs it into a CSV file. This would eliminate the faulty status being recorded in the OPC server to Historian path. Using the newly collected data, invariants can be generated using the association rule mining as done by (Umer *et al.*, 2017). Another direction would be to look into the possibility of merging the linear regression and association rule mining generated invariants of the system on the basis of a device.

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## VITA

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