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Statistical and predictive modeling of automated meter reading system outages

Prasad Prabhakar Shinde

STATISTICAL AND PREDICTIVE MODELING OF AUTOMATED METER READING SYSTEM OUTAGES

by

PRASAD PRABHAKAR SHINDE

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Dr. Mariesa L. Crow, Advisor
Dr. Badrul H. Chowdhury
Dr. Mehdi Ferdowsi

ABSTRACT

An Automated Meter Reading (AMR) system is a metering technology that enables power utility companies to receive customers' energy usage data centrally over a communication network. The installed automated meters also provide a daily log of outage events for each customer. A utility company can greatly benefit by using this information for outage management and to improve reliability. However, outage data is frequently corrupted and the outage flags registered by the customers' meters do not necessarily reflect true outages. This thesis focuses on developing methods to analyze outage data and building a model to identify good data versus spurious indications. Outage data analysis is accomplished by comparison with known occurrences of outage events. A histogram analysis is performed to study the distribution of multiple outages. This thesis also introduces a fuzzy logic-based algorithm to analyze AMR meter outages and predict a degree of accuracy for each outage indication. A generalized model is developed to gather essential network information pertinent to outage indications. This information is combined with data from the outage analysis system and is used as an input to the fuzzy logic system that analyzes the information and provides a confidence index for the AMR outage flags.

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I dedicate this thesis to my father and my advisor.

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1. INTRODUCTION

1.1. MOTIVATION

A major challenge for any electric power distribution company is outage detection and service restoration. A utility company typically has an outage management system that combines inputs from customer trouble calls, supervisory control and data acquisition (SCADA), automated meter reading (AMR) systems, and any relevant information known to the system operators. The automated meters of an AMR system report outages and provide data for outage analysis. The use of automated meters can significantly reduce outage restoration time and, in turn, system reliability can be improved. Unfortunately since distribution systems tend to be large and complex, it is common to not have a low level automated system for outage detection; therefore SCADA is usually limited below the substation level. Thus, without an AMR system, outage location is based mainly on customer trouble calls.

It has been observed that the outage data reported by AMR system meters is often corrupted with noise resulting in false outage indications. Thus the potentially valuable meter outage data cannot be directly used for outage management. This thesis presents an approach to analyze AMR outage data and uses fuzzy logic to model uncertainties in the outage status of customers.

1.2. AUTOMATED METER READING SYSTEMS

An automated meter reading (AMR) system is a metering technology that enables power utility companies to receive customers' power usage data centrally using a communication network. Existing AMR systems have traditionally used telephone lines for communication. However, recently developed AMR systems use power-lines, wireless radio network, telecommunication network, or a combination of these systems [5]. The AMR systems analyzed in this project communicate over a wireless network.

The primary role of AMR is to provide real time power usage information of each customer to the central system for billing and analysis. In addition to the consumption data, AMR may also provide additional services such as theft protection, data security, and outage notification. Some AMR systems send real-time outage notification and power restoration information [6]. If the AMR units are equipped with two-way communication capability, meter status data along with time stamps can be collected by polling the meters.

1.3. OUTAGE ANALYSIS SYSTEM

Every utility company has outage management practices for outage location and rapid outage restoration. At Ameren, there is an outage analysis system (OAS) that uses trouble calls from customers to identify outage locations and probable causes for outages. The utilities track the trouble calls as they are received and forward them to the OAS. The outage analysis system provides an interface for the operator to process the outages, and is used to maintain track of daily outages, causes, computation of extent of outage, and for attending to outages in a timely manner. An important function of the OAS is to predict which protective device is suspected to be open, and therefore, the root cause of an outage. This device is labeled in the system as the highest probable device (HPD).

The OAS has an extensive network and device database. The OAS database includes a list of every device, described by a device name, device type, phase, and the feeder name which serves this device. An operator logs outage jobs and notifications into the OAS. A typical outage order entry in OAS includes order number, order creation date and time, details of highest probable device and feeder number of outage location.

1.4. FUZZY LOGIC

Fuzzy logic is a multi-valued logic system that uses reasoning that is approximate rather than fixed and exact. Fuzzy logic is typically used to handle imprecision in data or when there is a need to implement generalized constraints. In other words, fuzzy logic is implemented when it is not possible to use rigid logical constraints such as truth table look up, as in Boolean algebra. Fuzzy logic uses a set of if-then rules to solve a problem.

The most important motivation to use fuzzy logic arises due to its ability to process data according to a degree of membership, rather than crisp classification into set membership or non-membership. In addition, fuzzy logic is flexible and hence it is easy to make changes to the designed system. Fuzzy logic can be built on human experience or expertise making the system adaptive. Fuzzy logic is tolerant of imprecise data and is based on natural language. Unlike crisp logic, a fuzzy logic output is not a discrete state of “high” or “low,” but is instead a continuous output space.

1.4.1. Membership Functions To understand the way input or output spaces are mapped in fuzzy logic, it is important to understand the simple concept of membership functions. A membership function is a curve that determines the amount of participation of each input in a given parameter space. An input space can be classified into two or more memberships and an input value does not have to belong to any one membership exclusively. Instead, an input or output value may have a degree of participation in one or more membership functions.

1.5. BACKGROUND IN OUTAGE ANALYSIS USING AMR SYSTEMS

Every utility has their outage management system for outage location and service restoration. The primary sources employed by outage management systems for data collection are trouble call management systems, distribution SCADA, and AMR systems. With developments in the metering technologies and communications network, utilities have begun to find outage management using AMR systems a very attractive option.

Sridharan and Schulz [1] detail the development of an information filter for automated metering systems. The filter prevents false outage notifications being fed to the outage management system. In an effort to improve the quality of outage data, the paper discusses modeling uncertainties involved in the query process of wireless automated meters. This uncertainty has been modeled using probabilistic and fuzzy engineering techniques. The automated meters from the metering system on which the work was performed had provisions of automated detection of outages and online restoration verification. An on-demand query is sent to the meters to verify the status of the service and to validate the outage data. The objective of the validation process is to validate the continued existence of each individual outage. The filter algorithm utilizes the probabilistic function and fuzzy logic modeling to compute the probability that the meter failed to communicate the restoration notification packet.

Liu and Yan, et. al. [2] propose using multiple outage information sources and combining the information from all sources for the purpose of outage management. They suggest that due to the complexity of the distribution system, no single data source can provide consistently accurate outage information. An outage data processing algorithm is proposed that can provide more accurate outage information for the estimation of fault locations by combining data from trouble calls, AMR, and distribution SCADA. A fuzzy logic algorithm is then used to model uncertainty and to reconcile conflicting data by combining information from all sources.

Automated metering systems have also found popular application in outage restoration processes. As reported in [3], [4], and [5], importance is placed on finding an algorithm to assist in the process of outage restoration, as in post-storm outage restoration. Researchers have used techniques of outage mapping, outage escalation, and have presented efficient meter polling algorithms for outage restoration confirmation. Choices of data validation are made based on the time of outage, time of meter polling, health of the meter, i.e. battery status or radio strength, and breaker information from the SCADA system.

The metering system from this thesis project imposes peculiar constraints, and poses challenges in application of regular outage analysis methods. Most of the work done in the field of outage analysis using AMR systems involves optimally sending a query to the automated meters to check if the outage still exists and then eliminating spurious outage notifications before applying outage analysis techniques. The AMR system used in this project does not have an option of polling the meters, and hence outage notifications have to be analyzed without confirmation of restoration. The outage data is received only once every 24 hours with no information on exact time of outage. The analysis methods and models developed in this thesis are specifically designed to meet the needs of the metering system described and employed by Ameren.

1.6. OUTLINE OF THESIS

This thesis is divided into four sections. The first section describes the motivation behind this thesis and introduces the AMR system, OAS system, fuzzy logic, and background work in outage management using AMR systems.

The second section concentrates on analysis of historic meter outage data and covers system data description and management. The results of analysis are also included.

The third section explains design steps and implementation of fuzzy logic system for analysis of meter outage data.

The final section describes the conclusions drawn from this work and future work recommendations.

2. ANALYSIS OF OUTAGE DATA

2.1. SYSTEM DATA MANAGEMENT

The outage analysis system has an extensive network and device database for outage management and analysis. This database contains detailed information about system devices and network configuration. The following section describes the data tables and their use in outage analysis.

The system under study is a radial distribution system. The power is carried through sub-transmission feeders originating at a substation and distributed by local feeders to customer locations. Each local feeder is supplied through a protection device such as a fuse, switch or recloser.

2.1.1. List of All Feeder Devices (JW_OAS_DEV2) - This file is a list of all the network devices with devices being grouped together with the respective local feeder. A device is specified by a device number, device type, main supply feeder, supply node number, and supply device phase. A local feeder is commonly known as a pseudo node.

Table 2.1 shows a few entries from the **JW_OAS_DEV2** data file.

Table 2.1 JW_OAS_DEV2

DEV_TYPE	DEV_NO	SUPPLY_FDR_CURR	SUPPLY_NODE_NUM	SUPPLY_DEV_PHASE
F	280055	280055		7
X	02090520005	280055		1
X	02090520014	280055		3
X	02090520048	280055		7
U	SL83811437	280055	A	3
X	02090520011	280055	A	3
U	SL83817016	280055	A1	3
X	02515540016	280055	A1	3
D	SL82817116	280055	F	7

Table 2.2 explains the nomenclature used in **JW_OAS_DEV2** data file. For example, the fifth (shaded) entry in Table 1 contains information for a device type of ‘fuse’ represented by letter ‘U’. The fuse identification number is ‘SL83811437’; it is served by sub-transmission feeder ‘280055’ and by sub-feeder ‘A’. The supply phase for this fuse is C-phase represented by number ‘3’.

Table 2.2 JW_OAS_DEV2 data table description

<table>
<tr><th colspan="2">DEV_TYPE</th><th>DEV_NO</th><th>SUPPLY_FDR_CURR</th><th>SUPPLY_NODE_NUM</th><th colspan="2">SUPPLY_DEV_PHASE</th></tr>
<tr><td colspan="2">TYPE OF DEVICE</td><td rowspan="9">UNIQUE DEVICE NUMBER</td><td rowspan="9">FEEDER NUMBER SUPPLYING DEVICE</td><td rowspan="7">PSEUDO NODE NUMBER</td><td colspan="2">DEVICE PHASE</td></tr>
<tr><td>F</td><td>FEEDER</td><td>1</td><td>A</td></tr>
<tr><td>R</td><td>RECLOSER</td><td>2</td><td>B</td></tr>
<tr><td>D</td><td>DEVICE (SWITCH)</td><td>3</td><td>C</td></tr>
<tr><td>U</td><td>FUSE</td><td>4</td><td>AB</td></tr>
<tr><td rowspan="4">X</td><td rowspan="4">TRANSFORMER</td><td>5</td><td>AC</td></tr>
<tr><td>6</td><td>BC</td></tr>
<tr><td rowspan="2">Note: not unique across all feeders</td><td>7</td><td>ABC</td></tr>
<tr><td>9</td><td>UNKNOWN</td></tr>
</table>

Using the information given in the JW_OAS_DEV2 file, a network diagram is sketched in Figure 2.1. Figure 2.1 show the feeder ‘FC’ portion of the network. Feeder ‘FC’ is a three phase feeder supplied by primary sub-feeder ‘F’. Feeder ‘F’ also serves other sub-feeders such as FA, FB, FC, FD, and so on (not shown in figure). Feeder ‘F’ is supplied by sub-transmission feeder 280055 (not shown in the figure). As can be seen from the figure 2.1, feeder ‘FC’ supplies power to feeders FC1, FC2, FC3, FC4, FC5, FC6, FC7 and FC8. It should be noted that every sub-feeder such as F, FC, FC6, etc. is also a supply node. Supply nodes are sub-feeders supplied by sub-transmission feeders such as ‘280055’. As can be seen transformer number ‘02090510003’ is served by ‘A’ phase of ‘FC’ feeder. Similarly, feeder ‘FC1’ is served by ‘C’ phase of ‘FC’ feeder through switch ‘SL81800769’.

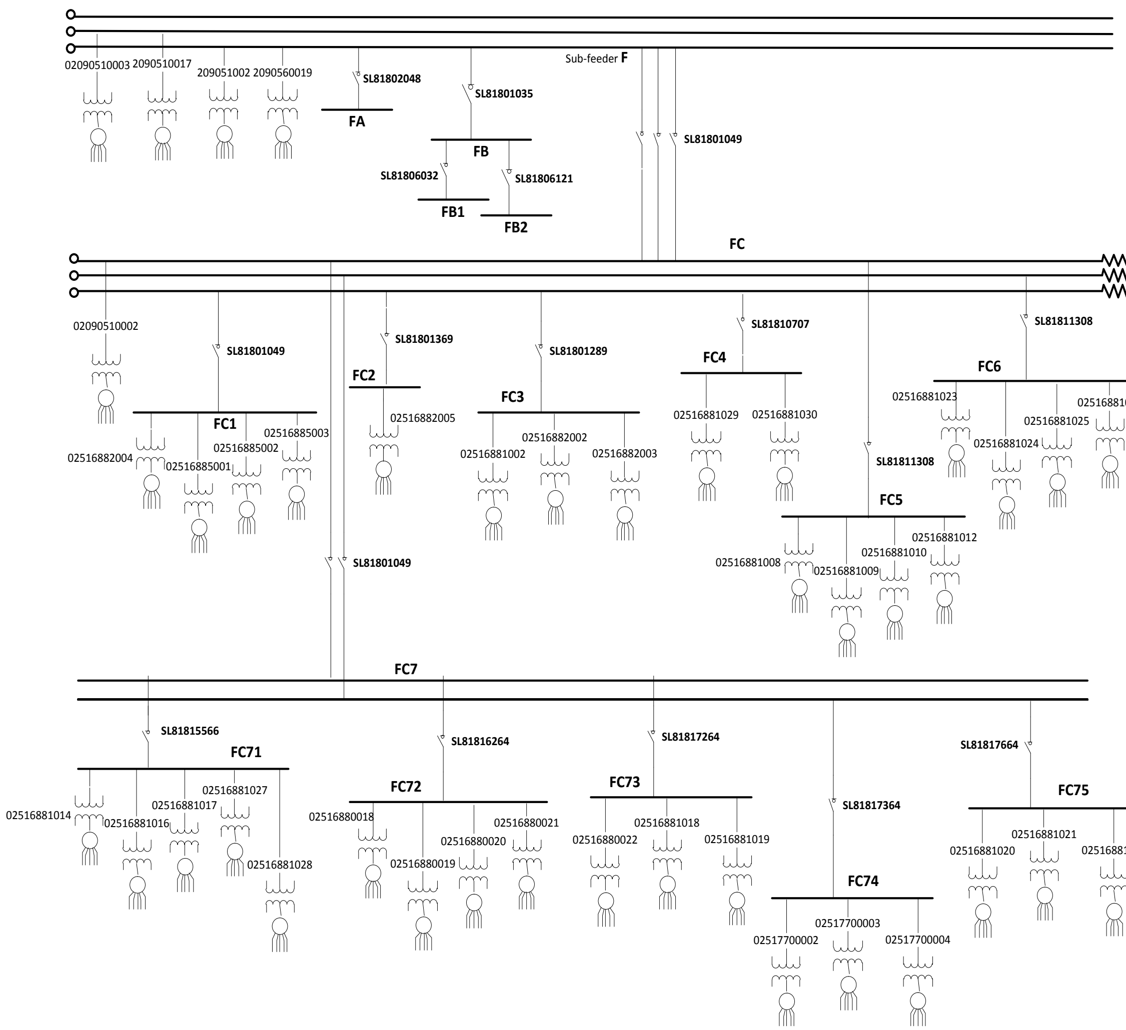


Figure 2.1 Feeder FC

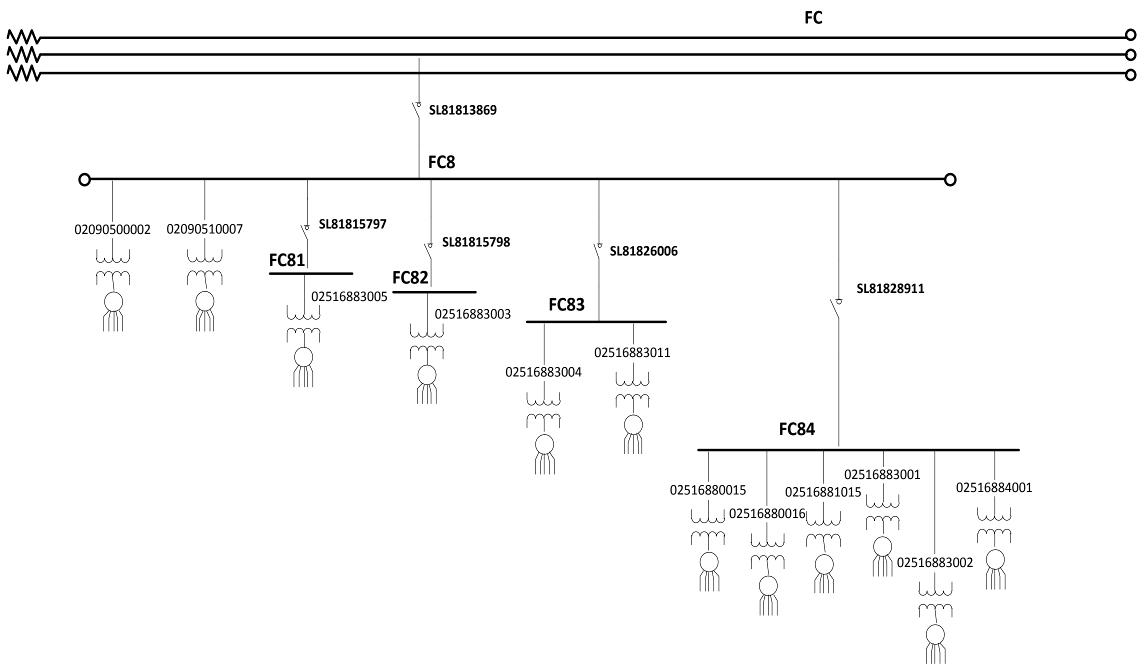


Figure 2.1 Feeder FC continued

2.1.2. List of Feeder Transformers (JW_OAS_XFMR2) - This file lists all of the transformers along with their respective supply feeder and supply node numbers. Table 2.3 shows a few entries from the **JW_OAS_XFMR2** database. Some of the transformers listed in Table 2.3 can be seen in the network diagram in Figure 2.1. For example, the first transformer in the table 2.3 (2090500002) is the leftmost transformer on node FC8 in Figure 2.1. This transformer is part of the 280055 circuit.

Table 2.3 JW_OAS_XFMR2

DEV_TYPE	DEV_NO	SUPPLY_FDR_CURR	SUPPLY_NODE_NUM
X	2090500002	280055	FC8
X	2090510002	280055	FC
X	2090520004	280055	G
X	2090520012	280055	A
X	2090520027	280055	0

2.1.3. Meter Outage Records (TME_MTR_XFMR2) - The meter outage data table contains records of daily outages received from the AMR meters. The AMR meters transmit an outage flag in an event of power loss. In case the meter experiences power loss multiple times, a total count of outages is transmitted. The meter is read approximately every 24 hours. The meter outage data table has details of meter numbers that experienced one or more outages, date on which the outage flag was received, the transformer number to which the meter is connected, number of daily outages, and the time at which the meter was read. In most cases, meters are read daily at 23:59 hours. It should be noted that the actual time of outage or duration of outage is not recorded.

Table 2.4 shows a few entries from **TME_MTR_XFMR2** table. Consider the first entry with meter ID number 18203464. This meter is connected to transformer 22624768041 (device type = X), supplied by ‘C’ phase (supply_dev_phase = 3) of sub-transmission feeder 475051 and supply node 9B56. The fault has occurred on 13-Feb-09 and the meter was read at 3:08:59PM. The flag of the meter is set to Y and quantity of daily outage is 1.

Table 2.4 TME_MTR_XFMR2

DEV_TYPE	DEV_NO	SUPPLY_FDR_CURR	SUPPLY_NODE_NUM	SUPPLY_DEV_PHASE	ID_MTR_SER_NO	DT_ACT_MTR_RDG	TM_ACT_MTR_RDG	FL_POWER_OUTAGE	QTY_DAILY_OUTAGE
X	22624768041	475051	9B56	3	18203464	13-Feb-09	3:08:59 PM	Y	1
X	02516880006	280055	F1	1	52699412	15-Feb-09	11:59:59 PM	Y	1
X	16924384088	465055	142121	1	31150215	15-Feb-09	11:59:59 PM	Y	51
X	22608768030	475051	9B56PA2	1	30362032	16-Feb-09	11:59:59 PM	Y	1
X	22624768003	475051	9B56K	2	18203465	16-Feb-09	11:59:59 PM	Y	1

The data field names and entries are described in Table 2.5.

Table 2.5 TME_MTR_XFMR2 data table description

DEV_TYPE	DEV_NO	SUPPLY_FDR_CURR	SUPPLY_NODE_NUM	SUPPLY_DEV_PHASE
X = TRANSFORMER	UNIQUE DEVICE NUMBER	FEEDER NUMBER DEVICE IS LOCATED ON	PSEUDO NODE NUMBER NOTE: NOT UNIQUE ACROSS ALL FEEDERS	DEVICE PHASE

ID_MTR_SER_NO	DT_ACT_MTR_RDG	TM_ACT_MTR_RDG	FL_POWER_OUTGE	QTY_DAILY_OUTGE
UNIQUE METER SERIAL NUMBER	DATE OF POWER OUTAGE FLAG NOTE: COULD BE FROM PREVIOUS DAY DUE TO 15 MIN TRANSMIT LAG	TIME INFORMATION WAS TRANSMITTED, NOT TIME OF OUTAGE	Y = POWER OUTAGE FLAG SET TO YES DURING PREVIOUS 24 HOUR PERIOD	NUMBER OF OUTAGES DURING PRIOR 24 HOUR PERIOD RECORDED BY METER COUNTER

2.1.4. List of Customers (JW_OAS_DEV_PHASE2) - This data file is a compilation of number of customers served by every transformer. Information about device phase, main supply feeder and supply node is also provided.

Table 2.6 shows a few entries from **JW_OAS_DEV_PHASE2** table.

Table 2.6 JW_OAS_DEV_PHASE2

DEV_TYPE	DEV_NO	DEV_PHASE	CUST_CNT_CURRENT	SUPPLY_FDR_CURR	SUPPLY_NODE_NUM	SUPPLY_DEV_PHASE
X	2090500002	2	0	280055	FC8	2
X	2090510002	1	0	280055	FC	1
X	2090510003	2	2	280055	F	2
X	2090510007	2	1	280055	FC8	2
X	2090510017	2	1	280055	F	2
X	2090510019	1	2	280055	F2	1
X	2090510020	2	2	280055	F4	2

CUST_CNT_CURRENT indicates the number of meters per device (transformer) per phase

2.1.5. OAS Outage Jobs (JW_OAS_ORDER_DETAIL) - OAS order detail is a database of outage orders from the Outage Analysis System (OAS). Every order is created with a unique order number and is provided with information about the order type, order creation date and time. An order type is identified for every outage job. A few examples of order types are Meter Job (MJ), Service Request (SR), and Mechanical Maintenance (MM). Amongst other information, JW_OAS_ORDER_DETAIL also provides the Highest Probable Device (HPD) for every outage entry. A device identified as an HPD can be a fuse, switch, recloser, transformer, or even the feeder itself.

Table 2.7 shows a few entries from file **JW_OAS_ORDER_DETAIL**

Table 2.7 JW_OAS_ORDER_DETAIL

ORDER_NO	CRTE_DATE	CRTE_TIME	ORDER_TYPE	HPD_DEV_TYPE	HPD_DEV_NO	HPD_DEV_PHASE	SUPPLY_FDR_CURR
90375029	2/6/2009	1814	MJ	X	16944400020	3	465055
90374621	2/6/2009	1500	SR	X	16016704028	2	646052
90426019	2/11/2009	1327	RC	X	2090520012	3	280055
90432725	2/12/2009	712	SL	X	2516882009	2	280055
90430215	2/12/2009	217	DC	X	2517700003	2	280055
90702598	3/8/2009	1105	MM	F	280055	7	280055
90696146	3/10/2009	1625	DO	U	SL80793413	1	280055

The data field names and entries are described in Table 2.8.

Table 2.8 JW_OAS_ORDER_DETAIL data table description

ORDER_NO	CRTE_DATE	CRTE_TIME	ORDER_TYPE	
UNIQUE OAS NUMBER	OAS ORDER CREATION DATE	OAS ORDER CREATION TIME	TYPE OF OUTAGE JOB	
ORDER NUMBER	DATE #	TIME	SO	SINGLE OUTAGE
			TO	TRANSFORMER OUTAGE
			DO	DEVICE OUTAGE
			FO	FEEDER OUTAGE
			GO	GROUPED OUTAGE
			MO	MAINENANCE OUTAGE
			PS	PARTIAL SECONDARY
			SR	SERVICE REQUEST
			SL	STREEL LIGHT
			RC	RECONNECT
			DC	DISCONNECT
			MM	MOMENTARY
			MJ	METER JOB
			RA	REPAIR ACTION

HPD_DEV_TYPE		HPD_DEV_NO	HPD_DEV_PHASE	SUPPLY_FDR_CURR
HIGHEST PROBABLE DEVICE TYPE THAT CAUSED THE OUTAGE		HIGHEST PROBABLE DEVICE THAT CAUSED THE OUTAGE	PHASE OF THE HIGHEST PROBABLE DEVICE THAT CAUSED THE OUTAGE	FEEDER NUMBER WHERE OUTAGE IS LOCATED
F	DISTRIBUTION FEEDER	DEVICE NUMBER	PHASE	FEEDER NUMBER
R	RECLOSER			
D	DEVICE (SWITCH)			
U	FUSE			
X	TRANSFORMER			
V	VOLTAGE REGULATOR			
A	SUBTRANSMISSION FEEDER			
B	SUBSTATION BUS			
C	LARGE CUSTOMER			

2.2. TOOL DEVELOPMENT

In a large network such as the one studied in this project, it is necessary to find a way to manage data with ease and to be able to extract pertinent information whenever needed. The function tools described in Table 2.9 were developed to search the data bases and return the salient information.

Table 2.9 List of Data Routines

Sr. No.	Function Name	Input	Return Values
1	meterdata	Meter number	Transformer number
			Pseudo node
			Device
			Phase
			Customer count
2	transformerdata	Transformer number	Pseudo node
			Device
			Phase
			Customer count
3	dev_connection	Device number	Up-stream devices
			Down-stream devices
4	OASmatching	Affected device list	Matched device list
		HPD	Un-matched device list

2.2.1. Meter Data Routine. This routine was created to access the relevant information for a meter. In the example below, the meter number is given as the input. The results obtained are transformer number, pseudo node, phase of the meter, and total number of customers connected to that transformer.

```
Input
mtrno=52699412;

Function
[trfno,pseudonode,phase,meters]=meterdata(mtrno)

Result
trfno      = 2516880006
pseudonode = F1
phase      = A
meters     = 9
```

Figure 2.2 Meter data routine example

In this example, meter number 52699412 was searched. The ‘meterdata’ function outputs the transformer number (‘trfno’) 2516880006, supply node (‘pseudonode’) ‘F1’, phase ‘A’, and a total of nine customers (‘meters’) on the same transformer.

2.2.2. Transformer data routine. For a transformer data routine, the input is the transformer number. The return values obtained are pseudo node, device number, the phase to which the transformer is connected, and the total number of customers connected to that transformer.

```
Input
trfno=02517700002;

Function
[pseudonode, device, ph,cust_count]=transformerdata(trfno)

Result
pseudonode =  FC74
device     =  SL81817364
ph         =  2
```

Figure 2.3: Transformer data routine example

In this example, transformer number 02517700002 is given as an input to ‘transformerdata’ routine. The results show that this transformer is served by phase-2 (phase-B) of node ‘FC74’ through device ‘SL81817364’, and that there are no customers served by this transformer.

2.2.3. Routine for Connection Information. The location of a device in the network can be determined by identifying the devices upstream and downstream to the given device. Since all the supply nodes are supplied directly by a device such as switch, fuse, or recloser, it is acceptable to consider all the transformers and devices served by a supply node to be connected to the device serving the supply node as well. For example, fuse **SL81801049** supplies power to node **FC** and thus every transformer or any other device immediately downstream to node **FC** can also be considered to be connected to fuse **SL81801049**. This is useful since supply node numbers are not unique across all feeders, whereas device numbers are unique.

```
Input
device = 'SL81813867'

Function
[USdev,DSdev]=dev_connection(device)

Result
USdev   =  'SL81801049'
           'SL82817116'
           '280055'
           '280055'

DSdev   =  'SL81815566'
           'SL81816264'
           'SL81817264'
           'SL81817364'
           'SL81817664'
```

Figure 2.4: Device connection routine example

Input to the function 'dev_connection' can be either a switch number, fuse number, transformer number, or any other device number from device database. This routine provides a list of device numbers upstream to the device in question (USdev) up to the sub-transmission feeder and a list of ID numbers of devices immediately downstream (DSdev). In the example shown in Figure 2.4, fuse ID **SL81813857** is given as input to 'dev_connection'. This fuse is connected to node **FC7** and the list DSdev has a list of all the devices directly served by **FC7**. For analysis purposes, it is assumed fuse **SL81813857** serves the downstream 'DSdev' devices instead of node **FC7** supply node numbers are not unique. The 'USdev' is a list of devices up-stream to fuse **SL81813857** with 'SL81801049' being the most immediate device that supplies power to FC7 and '280055' sub-station feeder being farthest up-stream device.

2.2.4. Routine for checking meter data with OAS data. This routine is developed to verify if a set of devices belong to the network supplied by highest probable device. A list of affected meters (and corresponding transformers) can be found from meter outage data. A highest probable device is found from the OAS records for corresponding date. The function identifies the devices that are part of the network under the HPD and develops two lists of either “true” or “false,” where true indicates that the device is a part of the network and false indicates that they are not.

Input

```
HPD=02090510007;
dev_affected=[02517700002, 02516880015, 02516883004, 02090520053];
```

Function

```
[true,false]=OASmatchingTrf(dev_affected,HPD)
```

Result

```
true =      2516880015              2516883004

false =     2517700002              2090520053
```

Figure 2.5: OAS matching routine example

In the example shown in Figure 2.5, the HPD provided was transformer ‘2090510007’. The meters with outages are supplied by the transformers given in the ‘dev_affected’ list. The function ‘OASmatchingTrf’ provides lists ‘true’ and ‘false’ where the first list is of transformers that are part of circuit downstream to HPD while ‘false’ is a list of rest of the transformers.

There is another function ‘OASmatchingsw’ which is used when the HPD is not a transformer, i.e., when the HPD is a switch, fuse, recloser or a sub-transmission feeder. The ‘dev_affected’ list is exclusively a list of transformer numbers.

2.3. DATA QUALITY

AMR systems used by all utilities have the same primary function of gathering customer power consumption data but differ in the auxiliary services provided. This section lists some of the shortcomings in the outage data information provided by automated meters of the AMR system under study.

Some of the data limitations include:

- **One way communication.** Most AMR systems have the on-demand read capability or the polling provision for wireless meters that can be used to enquire about the current status of the meter. By polling a meter, an operator can easily check if the power is on-line at a customer’s location. However, with the automated meters under study, only one way communication about meter outage status is possible. This limits the intelligence available about an outage and eliminates the possibility of identifying spurious outage flags.

- **Outage data is available only once a day.** Flag outage data is received once a day typically at close to midnight. This means that outage analysis is done just once looking at all the flags collectively. In AMR systems that receive outage data frequently at short intervals, it is easier to distinguish and analyze separate outage events.

- **There is no information on time of outage.** In the case where multiple meters show outages, it is difficult to discern if the outage events occurred simultaneously or at different times in a day as there is no time stamp available with flag indication. As 24 hours is a fairly long period between two meter readings, there is a chance of introduction of error in outage analysis if separate outage events are considered as dependent.

- **Low level distribution SCADA system not installed.** With advances in power system automation, supervision and monitoring is practiced widely in distribution systems as well. For the system under study, the SCADA system is installed only down to the sub-transmission level. System monitoring is not available at the distribution level in order to assist AMR flag data for outage analysis.

2.4. ANALYSIS OF HISTORIC METER OUTAGE DATA

The first task in developing a model for outage data analysis was to study the behavior of meter outage flags received in the past. If a meter experiences power outages during the period between meter readings, a meter outage flag is set and a daily outage count is recorded. Once the daily meter reading is conveyed, the flag is reset and the outage count is set to zero. The following two separate analyses were performed for these two outage information:

1) Validation Of Meter Outage Flag Indications
2) Histogram Analysis Of Daily Outage Counts

For this study, flag outage data from meters of sub-transmission feeder #280055 were considered and the duration of study is from 2/15/2009 through 2/12/2011.

2.4.1. Validation of Meter Outage Flags. In the absence of a monitoring system at the distribution level, the only source of information to assist analysis of meter outage data is the outage log of outage analysis system. Outage jobs and customer trouble calls are recorded in the OAS. To verify outage flag indications from meter outages, the highest probable device from OAS is used as a reference and the affected part of network is identified for analysis.

The following process is used to determine the accuracy of the outage data:

2.4.1.1. Outage Mapping. To check if the meter outages corroborate with OAS data, outages are mapped using network information. Outage mapping helps identify and analyze parts of the network that are affected. Using outage mapping, outages can be grouped and it is easier to validate cases of device failures. The highest probable device is used as a reference and the meters downstream to this device are considered to be most likely affected. In the example shown in Figure 2.6, the highest probable device is indicated with a green star and each fault indication is shown with red star. The algorithm using outage mapping is explained in section 2.3.1.3.

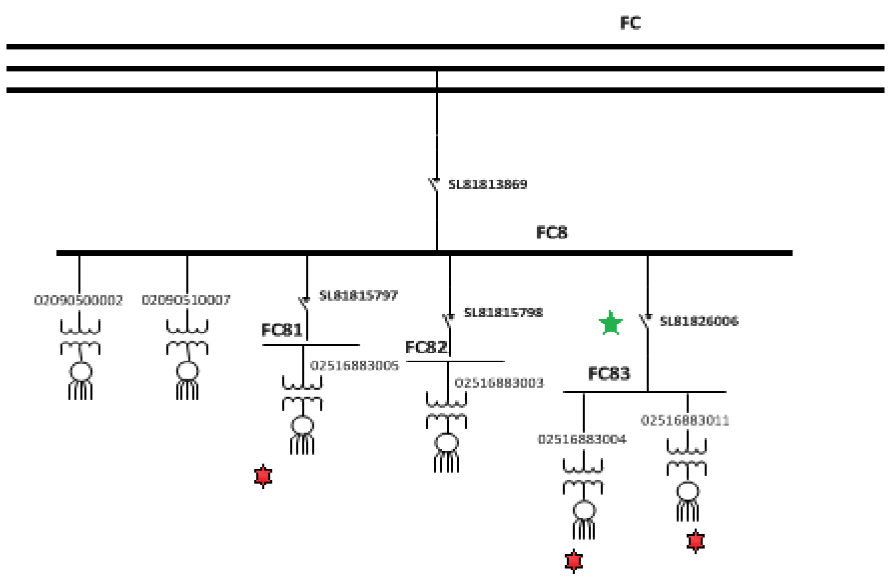


Figure 2.6: Outage mapping

Once outages are mapped out and their location is determined, the outaged nodes are grouped together and escalated up to the reference device to detect group outages. All outages are traced upwards in the network and a list of 'Affected Transformers' and 'Affected Devices' is determined with information of number of customers affected under each device and the phase on which they are located.

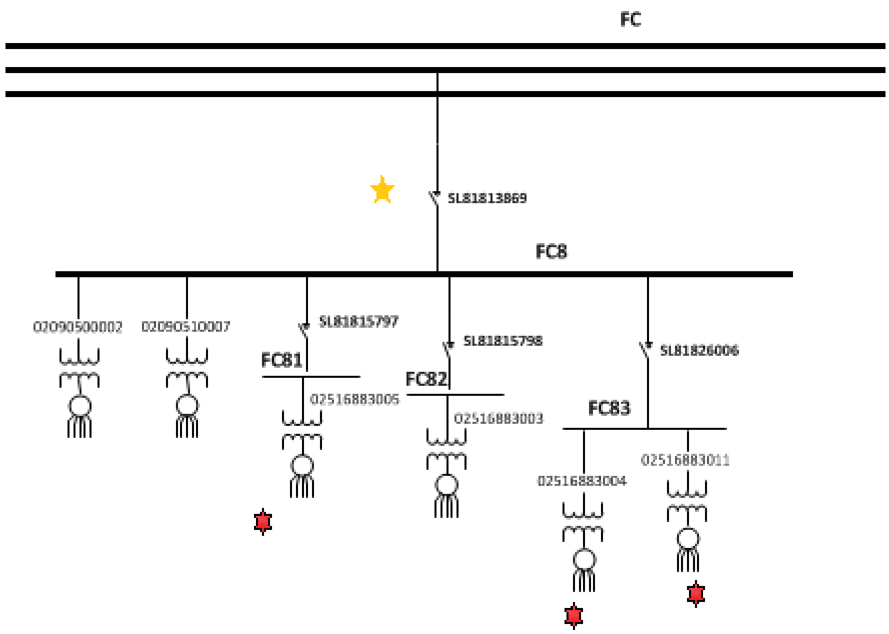


Figure 2.7: Outage escalation

2.4.1.2. Outage Validation. The OAS order detail database contains records of work orders for corrective and preventive actions on an outage. These order entries are under operator supervision and are considered a reliable source of information. The outage data received from the AMR is compared with the OAS outage data to check how often AMR system meters successfully correspond to recorded outage jobs.

The chart given in Figure 2.8 describes the algorithm used to determine if the outage data corroborates with OAS data.

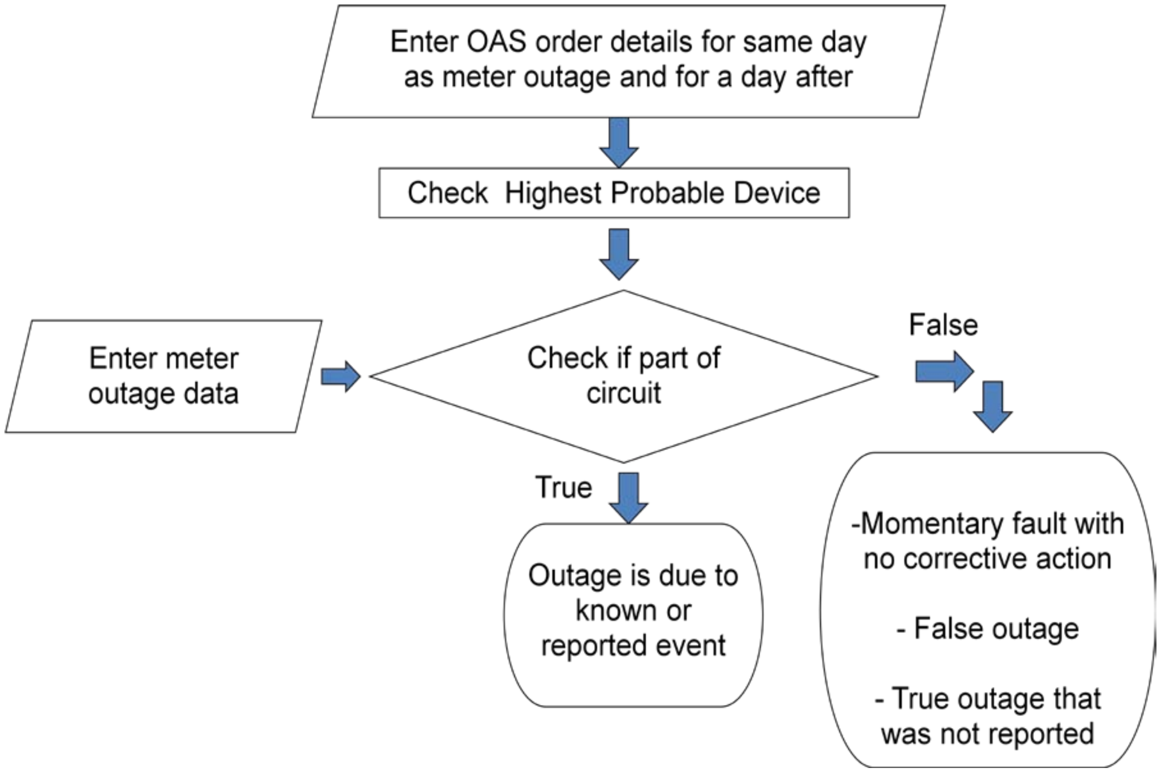


Figure 2.8: Outage validation algorithm

Meter outage data is received only once every 24 hours and is usually received around midnight while OAS orders can be generated at any time for a given date. The algorithm is developed to validate meter outages under the following two scenarios:

1) An operator becomes aware of an outage via trouble calls or some other source and creates an outage entry in the OAS system. The OAS analyzes this entry and determines a related highest probable device. If a meter supplied by this highest probable device reports an outage flag on the same day as the outage entry was made, then that outage indication is considered valid for correctly corresponding with the OAS records.

2) In the event that an outage indication from AMR meters does correspond with OAS, then it is possible that an outage event occurred but was not recorded in the OAS on the same day. This may happen if the outage occurred in the late hours or if it was not detected early on and hence there was no action taken on the same day. OAS data for the next day is included in the analysis considering that corrective action may not happen on the same day as the outage.

A list of highest probable devices is thus compiled over 2 days. Another list of meters showing outages is formed and the two lists are given as an input to the outage validation program. A database is built for every participating meter that has reported an outage flag, recording the results of outage validation.

2.4.1.3. Results. The results in Table 2.10 are for AMR meter outages studied from 2/12/2011 through 2/15/2011. These meters belong to sub-transmission feeder '280055'.

In case of multiple outages reported by a meter, the total count of daily outage is considered valid when they correspond with the OAS data. The meter success rate as a result of the outage validation is calculated separately in case of multiple outage indications.

Table 2.10: Results of outage validation

Meter ID	Total No. of days flags received	Total no. of flags received	No. of days meter data confirmed	No. of flags validated	Meter success rate per day basis (%)	Meter success rate overall (%)
52699412	70	119	4	6	5.71	5.04
52705013	26	41	1	1	3.85	2.44
52700183	138	666	6	31	4.35	4.65
52672316	6	6	2	2	33.33	33.33
30080965	5	5	2	2	40.00	40.00
52703255	5	6	1	1	20.00	16.67
52705149	13	15	4	5	30.77	33.33
52718207	8	9	2	2	25.00	22.22
52718214	7	7	2	2	28.57	28.57
52700243	34	36	3	4	8.82	11.11
56834077	6	6	2	2	33.33	33.33

98709865	7	7	2	2	28.57	28.57
52699370	3	3	1	1	33.33	33.33
52695592	7	7	2	2	28.57	28.57
52700192	6	8	3	3	50.00	37.50
52699434	2	2	1	1	50.00	50.00
52699418	4	4	2	2	50.00	50.00
56844339	6	6	1	1	16.67	16.67
52699530	7	7	2	2	28.57	28.57
60287427	5	5	1	1	20.00	20.00
52700446	7	7	2	2	28.57	28.57
52700328	7	8	2	2	28.57	25.00
52700330	6	6	2	2	33.33	33.33
52700324	6	6	2	2	33.33	33.33
52700316	5	5	1	1	20.00	20.00
52699494	6	6	1	1	16.67	16.67
52693620	17	19	1	1	5.88	5.26
52699179	3	3	1	1	33.33	33.33
52697169	7	7	1	1	14.29	14.29
52699482	6	6	1	1	16.67	16.67
52700340	6	6	1	1	16.67	16.67
52700202	5	5	1	1	20.00	20.00
52699510	5	5	1	1	20.00	20.00
52699497	6	6	1	1	16.67	16.67
52699404	3	3	1	1	33.33	33.33
52695305	5	5	1	1	20.00	20.00
52695280	6	6	1	1	16.67	16.67
58620863	6	6	2	2	33.33	33.33
17563149	9	13	2	4	22.22	30.77
52700244	4	4	2	2	50.00	50.00
52697120	6	6	2	2	33.33	33.33
98085368	6	6	2	2	33.33	33.33
52700321	4	4	1	1	25.00	25.00
52700210	6	6	1	1	16.67	16.67
52697135	2	2	1	1	50.00	50.00
52697134	4	4	1	1	25.00	25.00
52696164	3	3	1	1	33.33	33.33
52695603	5	5	2	2	40.00	40.00
52693619	6	6	1	1	16.67	16.67
52700213	7	9	1	1	14.29	11.11
52700326	6	6	1	1	16.67	16.67
52693621	6	6	1	1	16.67	16.67
52695227	6	6	1	1	16.67	16.67
52697161	5	5	1	1	20.00	20.00

52699402	5	5	1	1	20.00	20.00
52700179	5	5	1	1	20.00	20.00
52700344	6	6	1	1	16.67	16.67
52699470	4	4	1	1	25.00	25.00
52695231	6	6	1	1	16.67	16.67
52695273	5	5	1	1	20.00	20.00
39694732	5	5	1	1	20.00	20.00
52700241	7	7	1	1	14.29	14.29
52700260	5	5	1	1	20.00	20.00
56822751	6	6	2	2	33.33	33.33
52699425	5	5	1	1	20.00	20.00
52699508	5	5	1	1	20.00	20.00
52717568	8	8	2	2	25.00	25.00
52717572	9	9	2	2	22.22	22.22
52717341	8	8	2	2	25.00	25.00
52717226	6	6	2	2	33.33	33.33
52717176	7	7	2	2	28.57	28.57
52717182	4	4	2	2	50.00	50.00
52717564	7	7	2	2	28.57	28.57
52717584	8	8	2	2	25.00	25.00
52717593	6	7	1	2	16.67	28.57
52718227	5	5	1	1	20.00	20.00
97082909	8	8	2	2	25.00	25.00
58621176	7	7	2	2	28.57	28.57
52716691	8	8	2	2	25.00	25.00
52716730	7	7	1	1	14.29	14.29
52716843	5	5	2	2	40.00	40.00
52717342	7	7	2	2	28.57	28.57
52717585	11	14	2	5	18.18	35.71
52717360	7	7	2	2	28.57	28.57
52716712	5	5	2	2	40.00	40.00
52717325	7	7	2	2	28.57	28.57
52717359	7	7	2	2	28.57	28.57
52707772	8	8	2	2	25.00	25.00
31153253	7	7	2	2	28.57	28.57
18200861	7	7	2	2	28.57	28.57
52716721	6	6	2	2	33.33	33.33
52716734	5	5	2	2	40.00	40.00
52716718	5	5	2	2	40.00	40.00
52716707	6	6	1	1	16.67	16.67
52718047	7	7	2	2	28.57	28.57
63987799	7	7	3	3	42.86	42.86
52699388	8	8	4	4	50.00	50.00

52695300	8	9	4	5	50.00	55.56
21815152	7	7	4	4	57.14	57.14
52699174	7	7	4	4	57.14	57.14
52699293	8	8	4	4	50.00	50.00
52699321	8	8	4	4	50.00	50.00
52699387	7	9	4	4	57.14	44.44
52700181	8	8	4	4	50.00	50.00
52699382	8	8	4	4	50.00	50.00
98012600	6	6	3	3	50.00	50.00
52699351	4	4	2	2	50.00	50.00
52699270	7	9	3	3	42.86	33.33
52699231	12	16	2	4	16.67	25.00
52695459	7	7	3	3	42.86	42.86
52695446	3	3	1	1	33.33	33.33
98041526	6	6	3	3	50.00	50.00
52699279	7	7	3	3	42.86	42.86
52699197	6	6	3	3	50.00	50.00
52695544	7	7	3	3	42.86	42.86
52695478	4	4	2	2	50.00	50.00
77658360	6	6	3	3	50.00	50.00
52700212	5	5	2	2	40.00	40.00
52699234	5	5	1	1	20.00	20.00
52699183	3	3	2	2	66.67	66.67
52695453	5	5	1	1	20.00	20.00
52700315	4	4	1	1	25.00	25.00
34876158	5	5	1	1	20.00	20.00
52699310	3	3	2	2	66.67	66.67
52695590	6	6	2	2	33.33	33.33
52699504	6	6	1	1	16.67	16.67
30314189	5	5	1	1	20.00	20.00
52693976	6	6	1	1	16.67	16.67
52700317	6	6	2	2	33.33	33.33
25008634	5	5	1	1	20.00	20.00
98033224	6	6	1	1	16.67	16.67
52717365	1	1	1	1	100.00	100.00
52717614	171	886	17	58	9.94	6.55
22575947	7	7	2	2	28.57	28.57
98257531	6	6	2	2	33.33	33.33
22757712	6	6	2	2	33.33	33.33
52903827	6	6	2	2	33.33	33.33
55008822	6	7	2	3	33.33	42.86
91782841	5	8	2	4	40.00	50.00
17497478	6	6	2	2	33.33	33.33

88716843	6	6	2	2	33.33	33.33
94035727	5	8	2	4	40.00	50.00
89980165	6	7	2	3	33.33	42.86
89013453	5	6	2	3	40.00	50.00
89980188	8	9	3	4	37.50	44.44
17483478	6	7	2	3	33.33	42.86
30756052	6	7	2	3	33.33	42.86
56227046	6	7	2	3	33.33	42.86
92566031	6	7	2	3	33.33	42.86
91681868	5	8	2	4	40.00	50.00
39390341	6	7	2	3	33.33	42.86
94099790	5	8	2	4	40.00	50.00
94060910	5	8	2	4	40.00	50.00
80308504	6	7	2	3	33.33	42.86
88199904	6	7	2	3	33.33	42.86
85760286	6	7	2	3	33.33	42.86
35633578	4	4	2	2	50.00	50.00
52900964	10	10	0	0	0.00	0.00
49232055	9	10	4	5	44.44	50.00
87564379	9	12	3	3	33.33	25.00
52718189	13	16	4	5	30.77	31.25
35443388	29	277	1	17	3.45	6.14
48735058	6	7	2	3	33.33	42.86
68797186	8	10	2	2	25.00	20.00
96884509	5	6	1	1	20.00	16.67
52699452	8	8	3	3	37.50	37.50
52697147	12	14	1	1	8.33	7.14
52699193	26	33	1	1	3.85	3.03
52716672	24	28	6	7	25.00	25.00
52699204	57	72	7	10	12.28	13.89
52700246	8	8	1	1	12.50	12.50
52699474	20	27	0	0	0.00	0.00
94116295	6	9	3	3	50.00	33.33
52717363	8	8	3	3	37.50	37.50
52718230	8	9	3	3	37.50	33.33
81974971	8	8	3	3	37.50	37.50
52717358	6	7	2	2	33.33	28.57
28333285	3	2	2	1	66.67	50.00
52717370	8	8	3	3	37.50	37.50
52717372	8	8	3	3	37.50	37.50
52718211	7	8	3	3	42.86	37.50
52718259	10	13	3	3	30.00	23.08
87514223	7	7	3	3	42.86	42.86

52900959	7	7	3	3	42.86	42.86
60632561	5	6	2	2	40.00	33.33
52716732	7	7	3	3	42.86	42.86
52718237	8	8	3	3	37.50	37.50
52716727	6	7	3	3	50.00	42.86
66402172	5	6	2	2	40.00	33.33
52718222	8	8	3	3	37.50	37.50
52716699	6	7	3	3	50.00	42.86
49232486	7	7	3	3	42.86	42.86
94116293	6	9	3	3	50.00	33.33
18325153	7	7	3	3	42.86	42.86
44723917	6	6	3	3	50.00	50.00
52718239	8	11	3	3	37.50	27.27
52718243	6	7	3	3	50.00	42.86
56829886	7	7	3	3	42.86	42.86
52716698	6	7	3	3	50.00	42.86
52687224	6	6	3	3	50.00	50.00

It should be noted that only the first 150 (of 1301) entries from the result table are included in this thesis.

2.4.2. Histogram Analysis Of Daily Outage Counts. To study the distribution of multiple outage indications, a histogram analysis was performed on the AMR outage data. A histogram graph consists of frequencies of number of days on which multiple outages are reported, erected over corresponding outage quantity intervals or groups. Outage flags from a meter are grouped into intervals called outage quantity bins in order to accommodate a large range. These bins are usually of equal width. A frequency distribution plot, such as a histogram, provides valuable insight on the trend and likelihood of receiving a single or multiple outage flags per day.

The following study was done on meters supplied by feeder #280055. Furthermore, only those meters that have shown considerably high outages were analyzed. Outage data from meters was analyzed if the quantity of outage flags reported by a meter exceeded a daily outage count of 10 on at least one day or if the total outage flags reported by a meter during the entire period of study exceeded a count of 50.

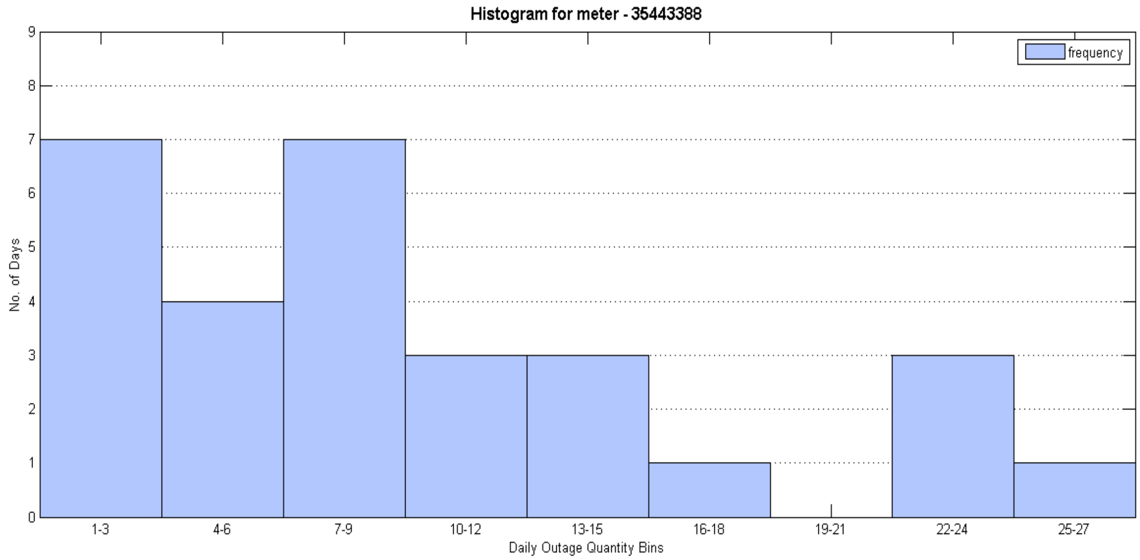
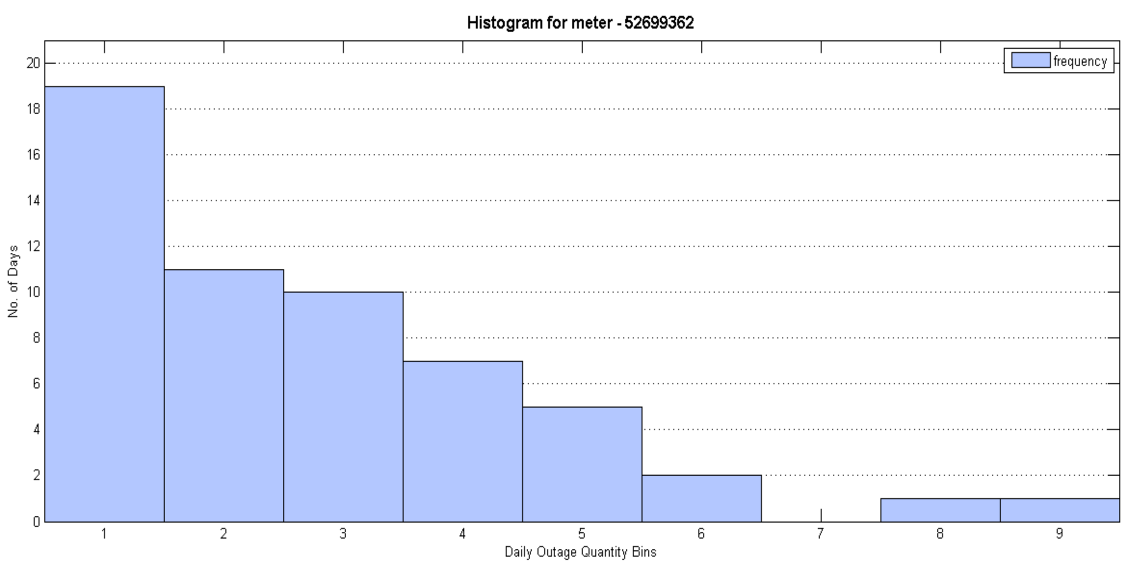


Figure 2.9 Histogram analysis plots

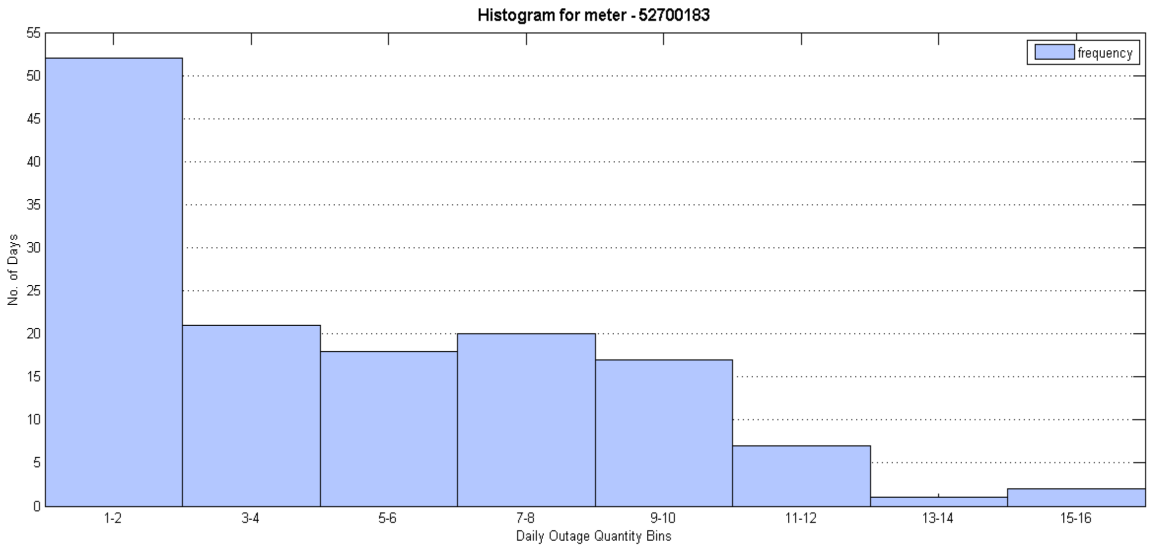
a. Histogram plot for meter #35443388

The outage count bins are all of interval 3. As seen from the graph, meter #35443388 has reported outages between counts of one to three on 7 different days. The maximum daily outage count reported by this meter was 27 on a single occasion.

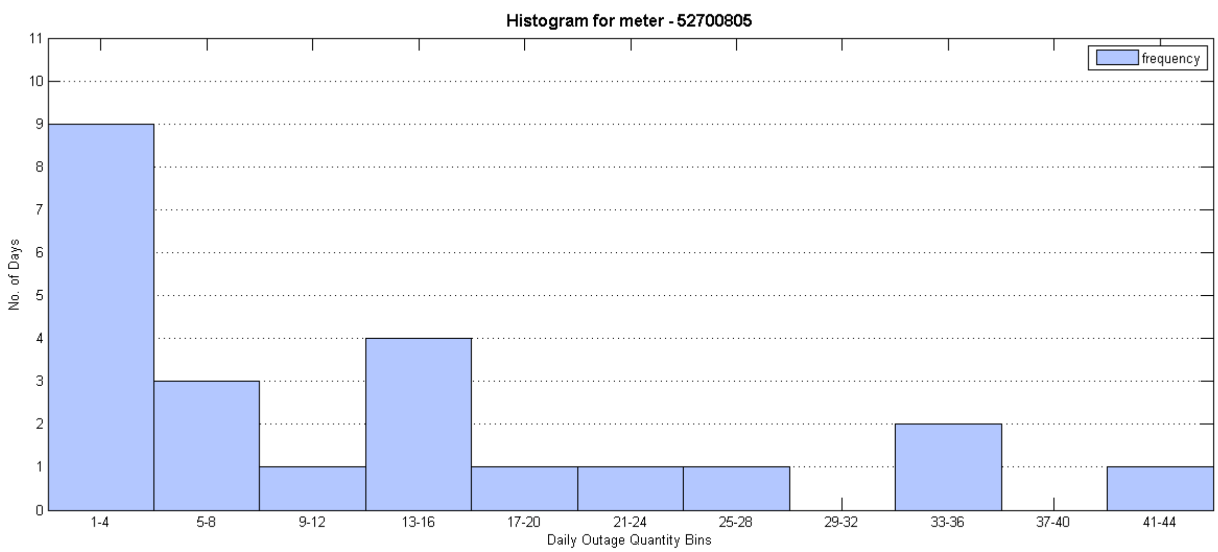


b Histogram analysis plot for meter #52699362.

The maximum daily outage count for meter #52699362 is 9 and was reported on a single occasion. A single outage was reported on 19 separate days.

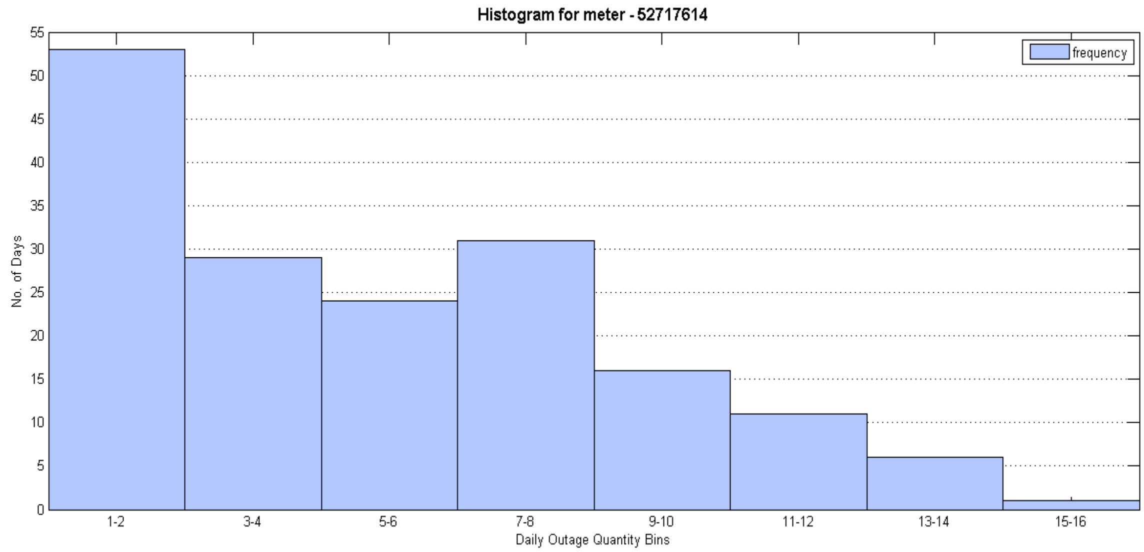


c Histogram analysis plot for meter #52700183



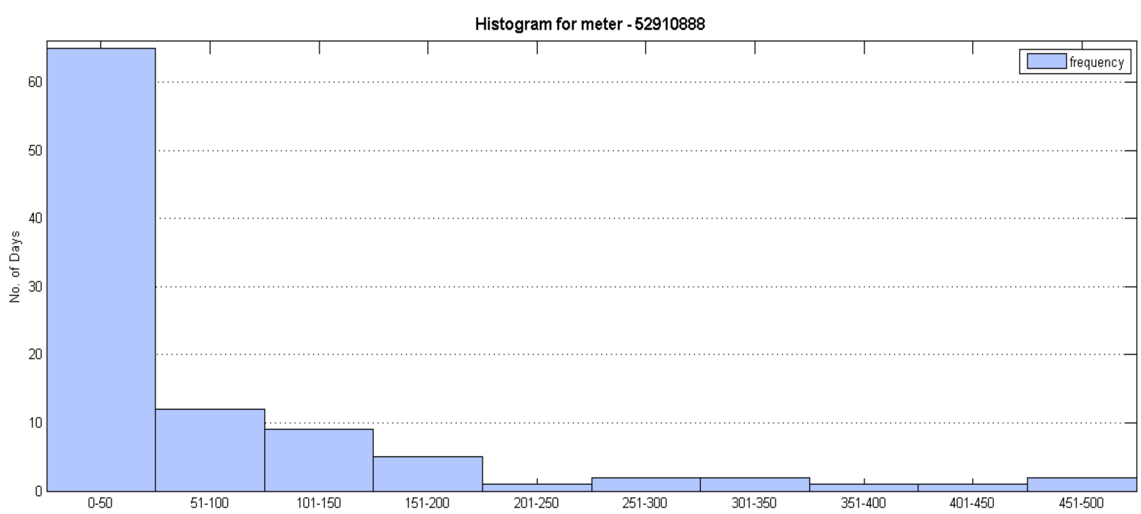
d Histogram analysis plot for meter #52700805

Meter #52700805 has reported a maximum of 44 outages in a single day. The outage count bins are grouped for 4 counts each.



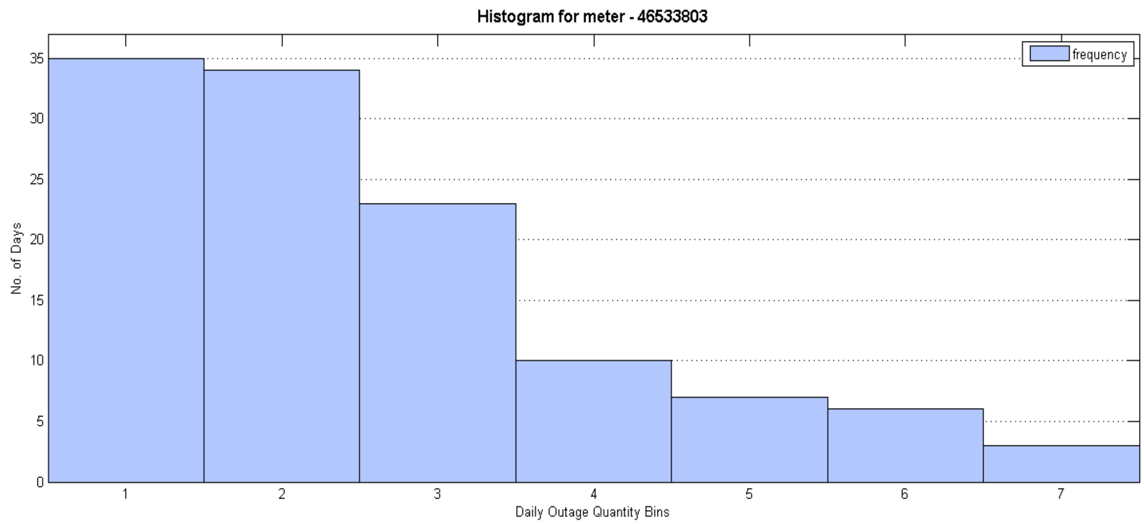
e Histogram analysis plot for meter #52717614

Meter #52717614 has reported a total of 886 flags on 171 different days with a maximum of 15 outages in a day.

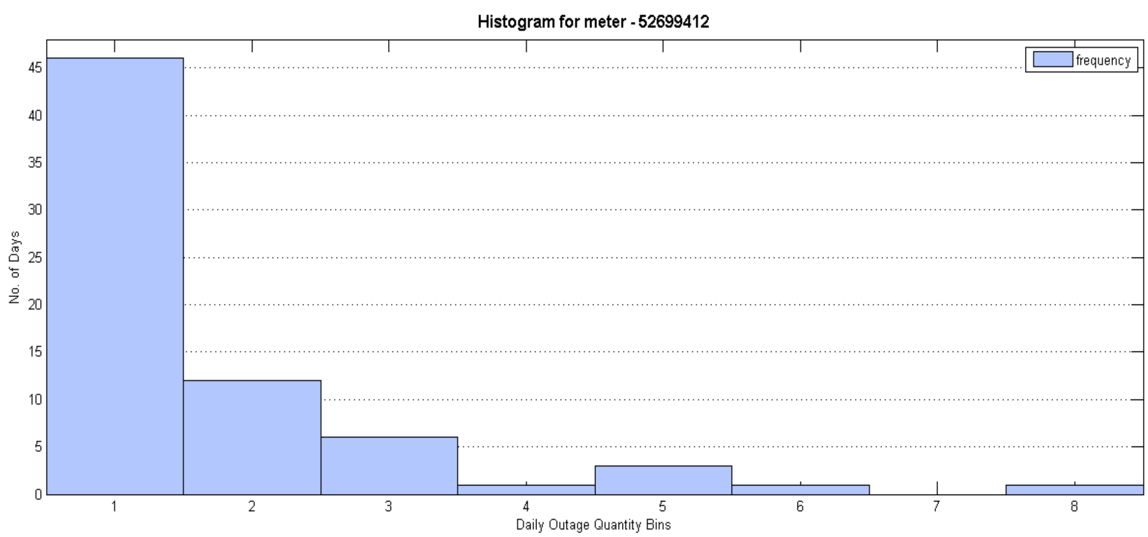


f Histogram analysis plot for meter #52910888

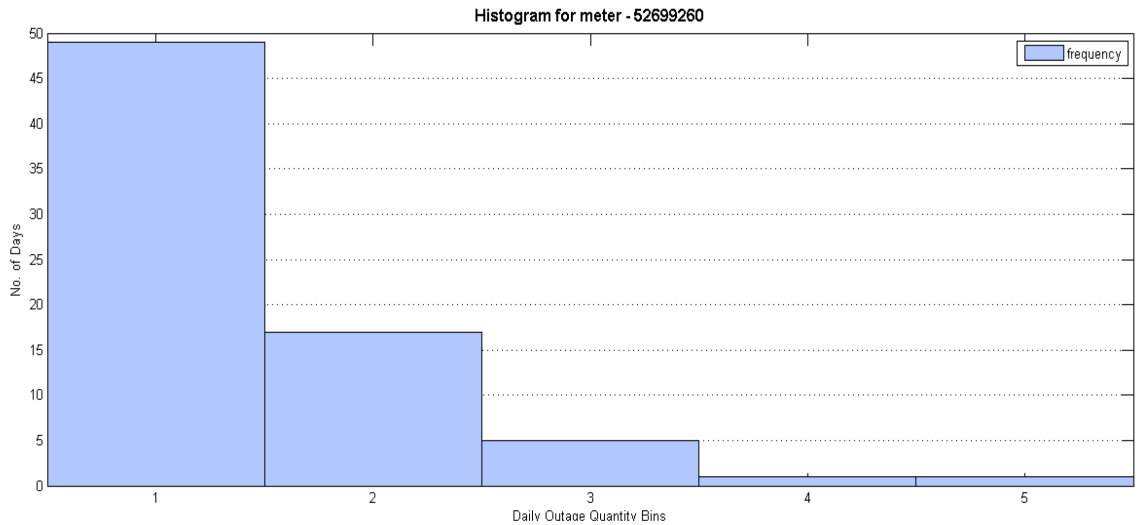
Meter #52910888has reported 6859 outage flags in hundred days with a maximum daily outage count of 489.



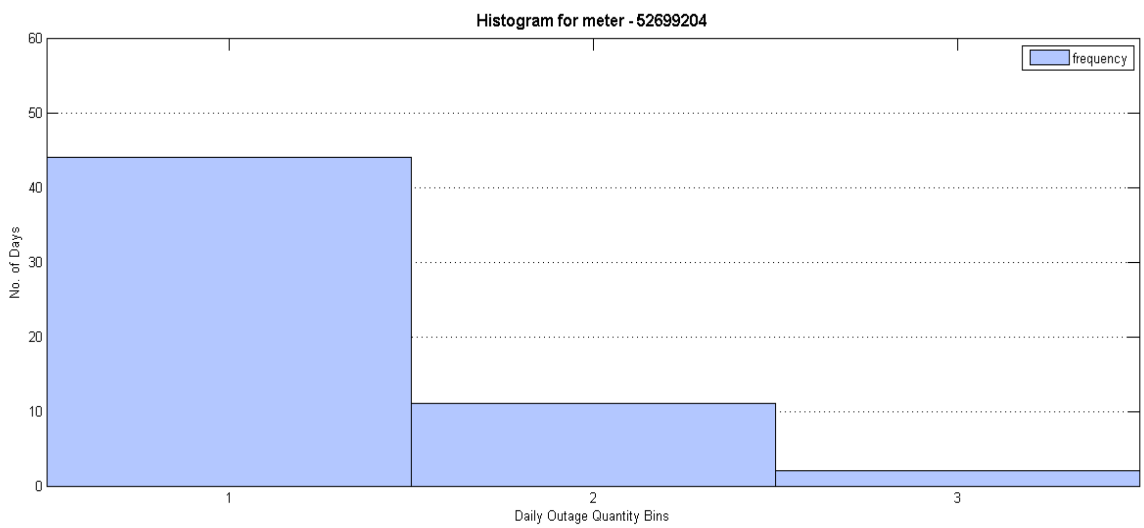
g Histogram analysis plot for meter #46533803



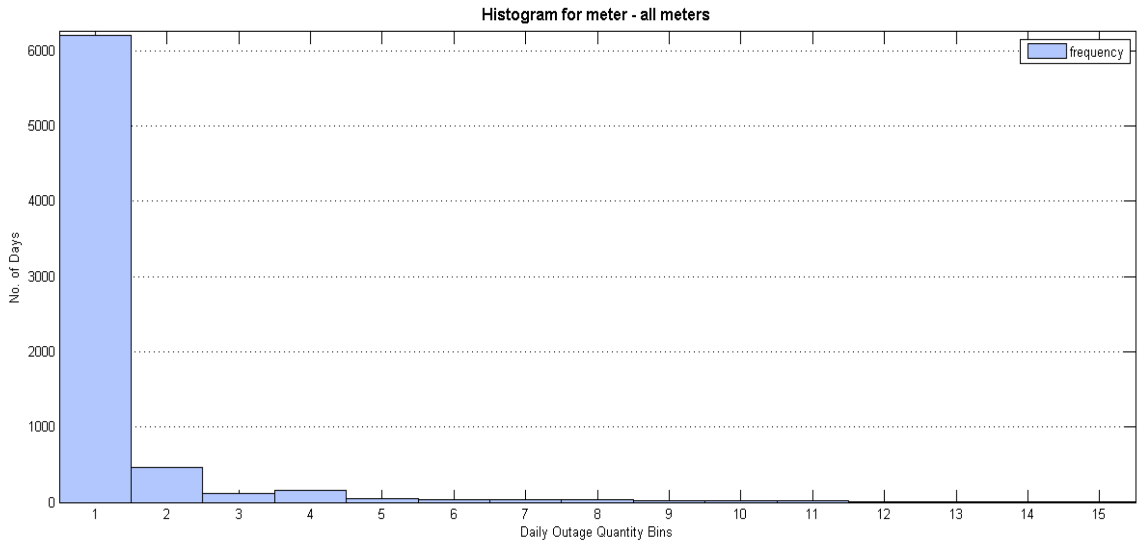
h Histogram analysis plot for meter #52699412



i Histogram analysis plot for meter #52699260



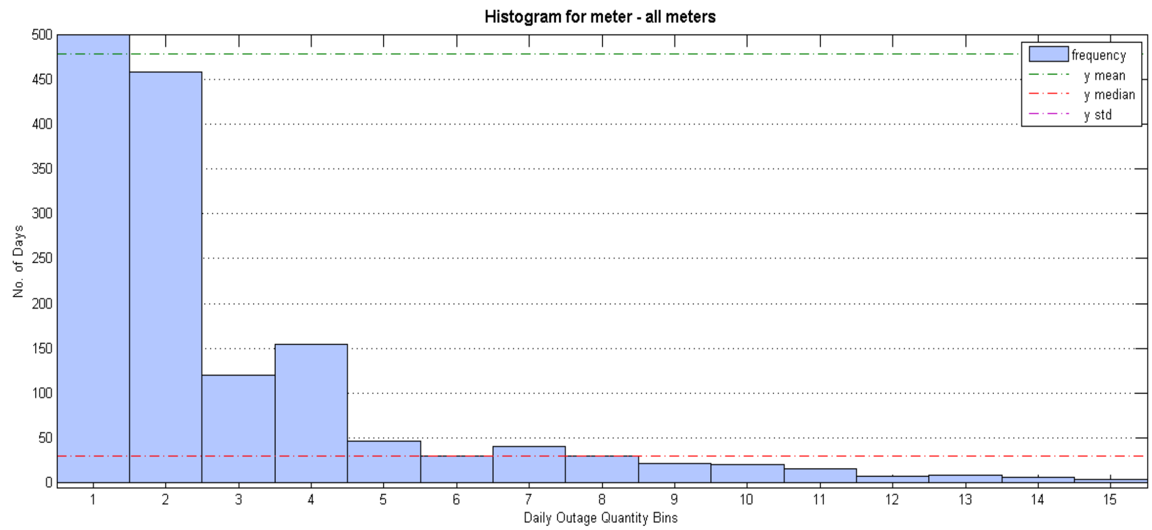
j Histogram analysis plot for meter #52699204



k. Histogram analysis plot for all meters (up to 15 outage counts)

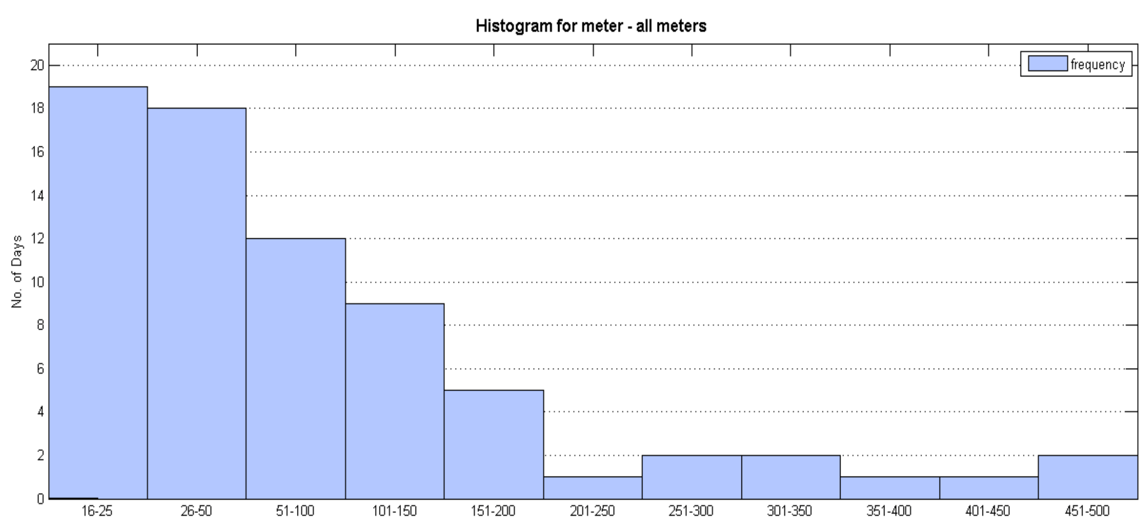
The maximum outage count shown by any meter for a day is 489. The histogram plot for all meter outages combined is divided into two ranges for daily outage count. As seen from the analysis, the maximum outage quantity for most meters does not exceed 15. Most of the data points are distributed in the range of 1 to 15 and is the most useful range for analysis. Including the whole range on a single graph disrupts the visual information and also necessitates creating bins of large size which can make the graph less intelligible. The histogram graph of Figure 2.9k has a sensitive slope and hence creating outage count intervals of even width two would greatly change the information demonstrated.

The frequency of receiving a single outage for all meters put together is 6202. As seen from the graph, the frequency of receiving multiple outages reduces as the outage count increases.



l. Histogram analysis plot for all meters (with median and mean)

The graph in Figure 2.9l is a part of graph in Figure 2.9k. This graph shows the median for frequency of days to be 30 and the mean is 478. As it can be seen from the graph, outage counts of 6 and 8 were reported on 30 separate occasions when meter outages were read. This does not necessarily imply that outage counts of 6 or 8 were reported on 30 different days.



m. Histogram analysis plot for all meters (counts 16 and above)

2.5. CONCLUSION

In order to analyze historic AMR outage data, meter data was compared with the outage analysis system data. The outage flag data was statistically modeled and a database was built to indicate the ability of the meters to report good data. The results of the analysis of the meter outage data provides a means to identify faulty meters that make up for most of the faulty data. Replacing or fixing even a few of these meters may help in severely reducing the amount of false readings. This analysis was specifically performed for AMR meters that do not have a polling option. Furthermore, the outage flag data was missing information regarding time of outage. Meter compliance records obtained from this analysis can serve as an indicator for future analysis of flags reported from these meters. The tools developed for data management can be used for other outage analysis models.

A histogram analysis was performed on the AMR outage data, in order to study the distribution of multiple outage indications. The distribution of outages in the histogram plots for all meters was observed to be highly right skewed. The frequency of receiving a multiple outage count decreases as the outage quantity increases. In other words, most plots observe a decaying frequency curve. A maximum daily outage count reported for every meter is different and it was observed that this count is usually below 15 with very few meters being an exception. A histogram plot for all meter outages put together over a range of 1 to 15 counts, shows that the median for frequency is observed in the range from 4 to 8.

3. FUZZY LOGIC BASED MODEL FOR OUTAGE ANALYSIS

A fuzzy logic based model was developed in this project to estimate a confidence index in outages reported by AMR system meters. The outage data received from AMR system meters tends to be erroneous and masked with noise. Fuzzy logic is a natural choice to filter this data, as systems built on fuzzy logic can handle imprecision and variation in input. The fuzzy inference system is a way of mapping the input space, containing information about the outage, to the output space. This mapping is done based on the formulation of fuzzy rules. The output is defuzzified to obtain a crisp value for confidence index, which represents the level of certainty that can be imparted to an outage indication.

Figure 3.1 is an overview of a fuzzy logic system showing the inputs to the system on the left being passed to the fuzzy logic engine and an output space on the right.

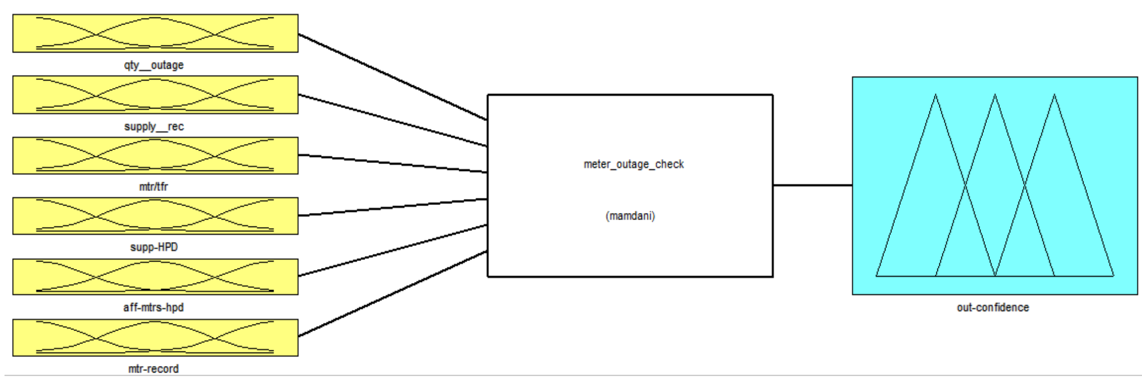


Figure 3.1. Fuzzy logic system overview

The first step in implementing fuzzy logic is to assemble a set of information that can serve as pertinent input to the fuzzy system. To make the most out of the decision making process, outage information received from the AMR outage data is combined with the knowledge of outage events recorded in OAS order details and network information. Every input to the fuzzy system is described in detail in section 3.1.

3.1. INPUTS TO THE FUZZY LOGIC ENGINE

The inputs to the fuzzy logic engine include daily outage count, recloser supply status for a meter, total number of meters reporting outage on a common transformer, historic meter records, HPD supply status, and total number of devices affected under the HPD. A routine is developed to quickly and conveniently compile all this information for every meter outage, and to pass it on to the fuzzy inference system.

3.1.1. Number of outage flags in a day. A meter can experience multiple outages in a day. When entering the daily outage count as an input to the fuzzy engine, information of whether a meter is supplied by a recloser is provided as well. The membership function graphs for these inputs are as shown in Figure 3.2.

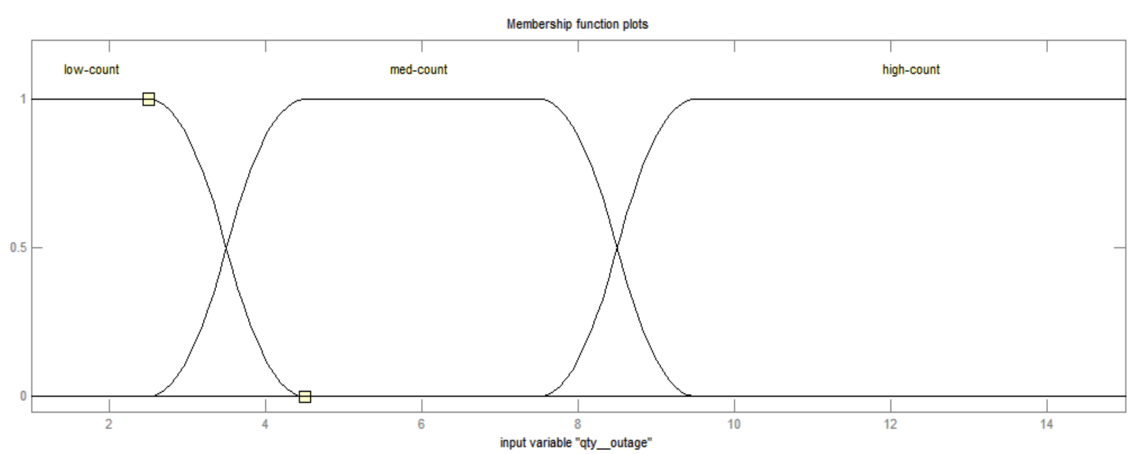


Figure 3.2.Membership function plot for input ‘daily outage quantity’

Here the input membership function is made of three curves namely low-count, med-count, and high-count. The division of input space into low, medium, and high regions was done based on the observations from histogram analysis performed on the historic data. It was observed that outage counts of one and two are reported most frequently, while the median lies in the range of five to eight daily outage counts. Fifteen or more daily outages are rarely reported.

The low-count input membership function is a z-curve, mainly including outage counts of one or two. The med-count input membership pi-curve encompasses outage counts of four through eight, while the high-count membership s-curve has full membership for outage counts of ten and above.

Along with information about number of outages reported by a meter, it is important to know if the meter is supplied by a recloser. A recloser is a protective device that has the mechanism to automatically close after it has been opened due to a fault. A recloser attempts to keep the circuit live after a momentary fault. If the fault persists after repeated attempts, the recloser opens its contacts and clears the fault. Thus a meter supplied by a recloser may see several power outages due to recloser action as opposed to a meter that is not supplied by a recloser which would register only one outage count for a similar event. This requires the meter outages to be modeled with additional information about the supply status by reclosers. The analysis model accounts for the increased possibility of receiving multiple outages by meters supplied by reclosers.

The following membership tells if a meter is supplied by a recloser.

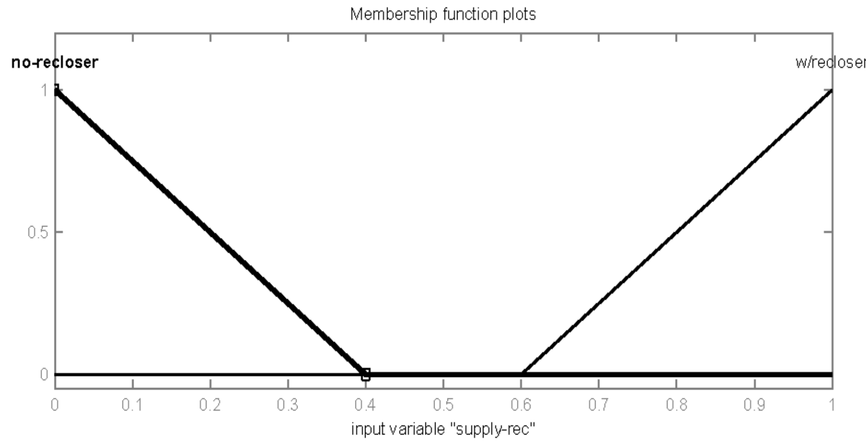


Figure 3.3.Membership function plot for input ‘supply by recloser’

When the input variable ‘supply-rec’ is 1 indicating that a meter is supplied by a recloser, membership for ‘w/recloser’ curve becomes 1. Similarly, when the input variable ‘supply-rec’ is 0 indicating that a meter is not supplied by a recloser, membership for ‘no-recloser’ curve becomes 1.

3.1.2. Number of affected meters on a transformer. A list of all affected meters is obtained from the AMR outage data and the meters are grouped under respective transformers. This information is useful in detecting group outages or local outages. The membership function for this input is shown in Figure 3.4.

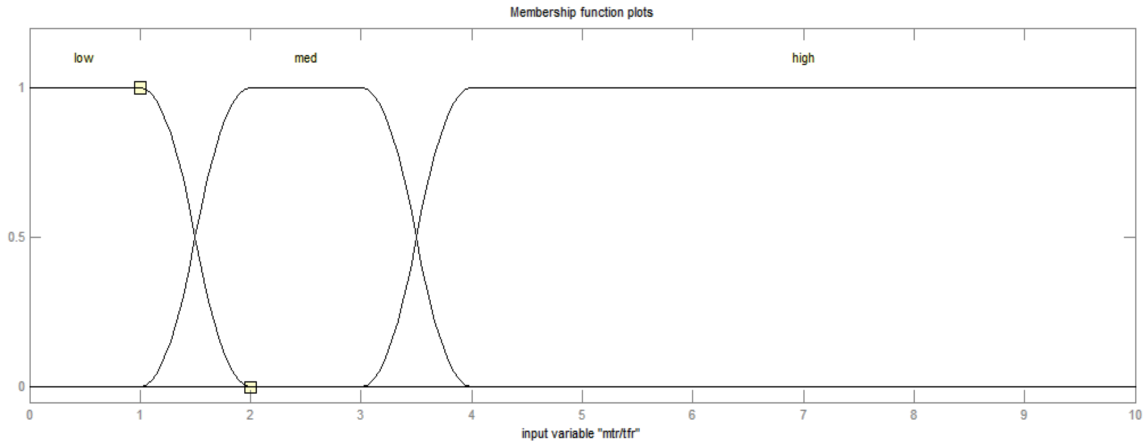


Figure 3.4 Membership function for input 'number of meters per transformer'

This input has three memberships of low, medium, and high. The utility considers two or more customer outages on a transformer as a group outage and hence the medium region begins at two outages on a single transformer.

3.1.3. Supply by Highest Probable Device. A highest probable device is identified by the OAS as the device that is most likely at the root cause of an outage. Thus an outage flag indication from the meters that are supplied by highest probable devices can be treated more credibly. In addition to this, grouping affected meters under every HPD can identify possible group outages.

The membership function shown in Figure 3.5 tells the fuzzy engine whether or not a meter is supplied by a HPD.

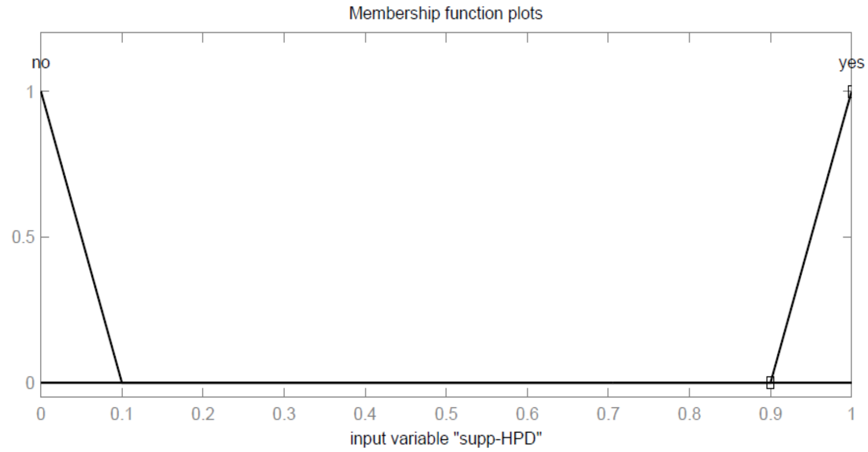


Figure 3.5 Membership function plot for input ‘supplied by HPD’

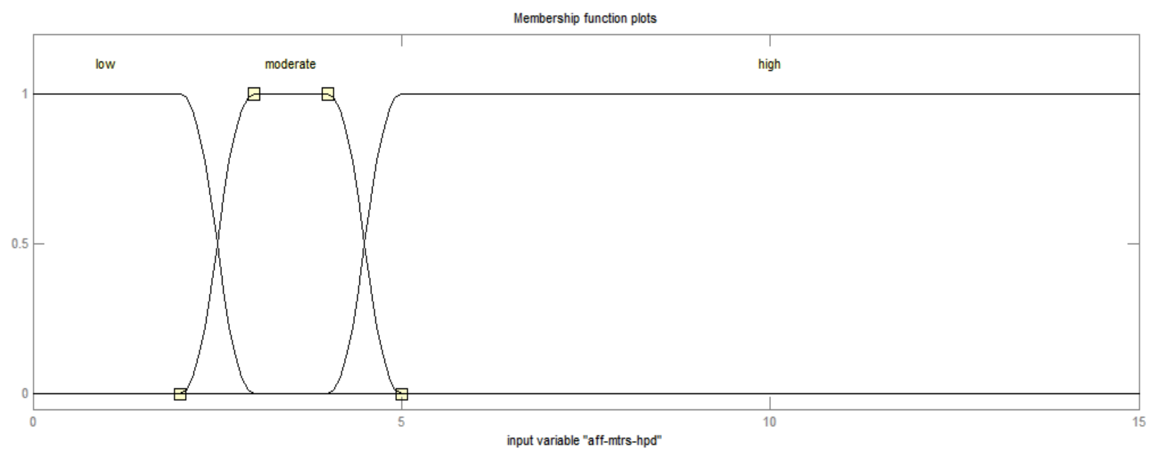


Figure 3.6 Membership function plot for input ‘affected meters per HPD’

The input shown in Figure 3.6 is classified into three membership functions of low, moderate and high. The ‘low’ membership function is a z-curve that spans a range of approximately zero to three meters affected under a HPD. The 'moderate' membership function is a pi-curve that includes a range of three to five and the high membership curve includes a range of approximately four to fifteen.

3.1.4. Meter records. This input is based on the results obtained from historical AMR outage data. A database was created for AMR meters, recording the number of times the reported outage flags corroborated with the OAS data. In other words, this database is a record of every participating meter's success rate in reporting correct outage information.

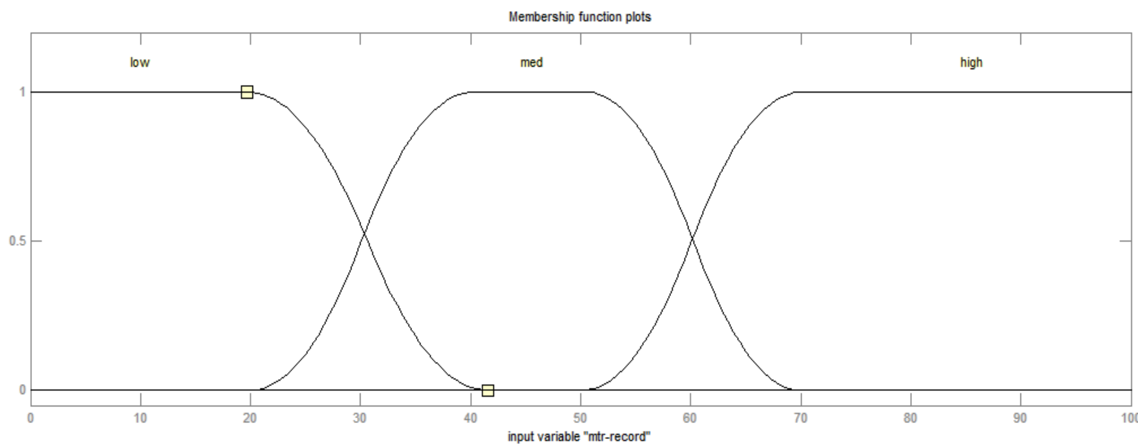


Figure 3.7 Membership function plot for input 'meter record'

Depending on a meter's past accuracy performance, the input meter record will have a relative membership in low, med or high memberships. The range for this input is from 0 to 100%.

3.2. OUTPUT MEMBERSHIP FUNCTION

The output space is divided equally in three membership functions: low, medium, and high. The membership functions low, med, and high are of the shape z, pi, and s respectively. The output range for confidence index is from 0 to 100 % and shown in Figure 3.8.

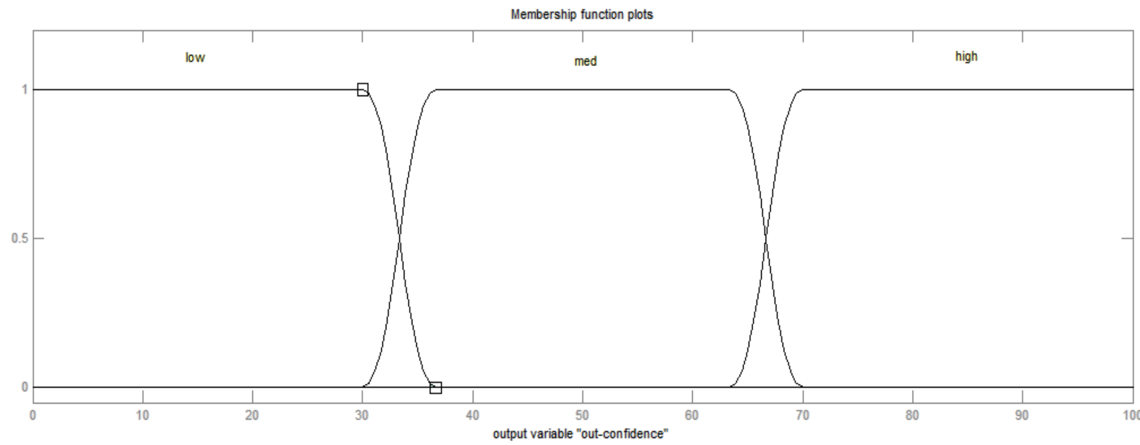


Figure 3.8 Membership function plot for output ‘confidence index’

3.3. FUZZY LOGIC RULES

The most essential part of the fuzzy system is the set of fuzzy rules that form the main logic used to formulate the mapping of a given input to an output. The fuzzy logic is a combination of logical operations and if-then rules. These if-then rules are designed to map input membership functions to corresponding output memberships while assigning a certain weight to each rule. These rules are constructed based on analytical study of the given input data.

3.3.1. Outage Quantity & Recloser Supply Status. Considering the daily outage quantity and recloser supply conditions, the logical conditions given in Table 3.1 are formulated. These inputs will be linked to one of the output memberships based on fuzzy logic and input conditions.

Table 3.1 Rules for input #1 and #2

Outage Quantity	**Logical Operator**	**Supply by recloser**	**Output**	**Weight**
Membership		Membership	Membership	
High	&	No	Low	1
High	&	Yes	Med	1
Med	&	No	Med	1
Med	&	Yes	High	1
Low	&	No	High	0.9
Low	&	Yes	High	0.9

A high outage count from a meter not supplied by a recloser is linked to the low of the output. Similarly, if a meter that is supplied by a recloser, reports outages in the medium or low region, then the confidence index is high. The rules for cases of low outage counts are given a weight of 0.9 because these rules are primarily designed for cases of multiple outages and the effects of a recloser on multiple outages.

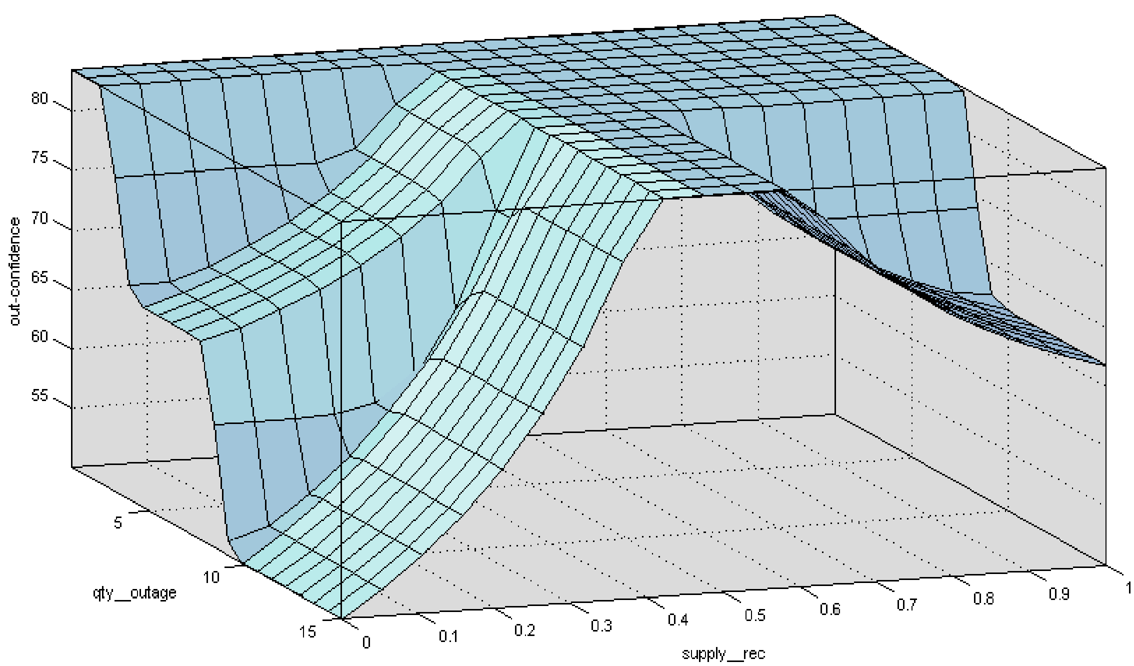


Figure 3.9 Surface for inputs outage quantity and recloser supply status

The rule surface for mapping inputs: outage quantity, and recloser supply status to output is shown in Figure 3.9. The input supply_rec can only have a value of 0 or 1. The plot is consequently meaningful only on the edges where supply_rec is either 0 or 1. It can be seen that the confidence index goes from high to low as the daily outage count increases.

3.3.2. Number of Affected Meters on a Transformer. Once the number of affected meters on a single transformer is determined, it becomes fairly straightforward to map this input to output. The rules formulating this mapping are given in Table 3.2.

Table 3.2 Rules for input #3

Number of meters per transformer	Output	Weight
Membership	Membership	
High	High	1
Med	Med	1
Low	Low	1

The rule surface mapping this input to output is shown in Figure 3.10.

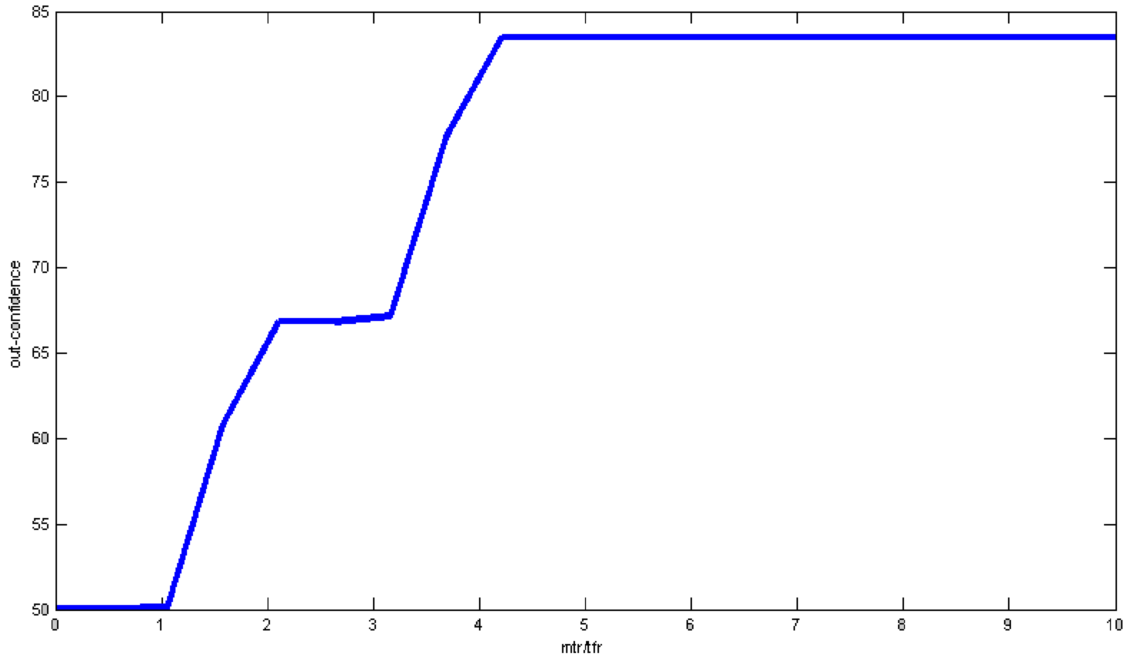


Figure 3.10 Surface for input meter per transformer

3.3.3. Supply by Highest Probable Device. This input can be coupled with the total number of affected meters under a HPD to formulate fuzzy rules. It should be noted that the necessary condition for this input to be useful for decision making is when the affected meter is downstream to at least one HPD. The rules governing this mapping are given in Table 3.3.

Table 3.3 Rules for input 3 and 4

Meter supplied by HPD?	Logical Operator	No. of meters per HPD	Output	Weight
Membership		Membership	Membership	
Yes	&	Low	Low	1
Yes	&	Moderate	Med	1
Yes	&	High	High	1

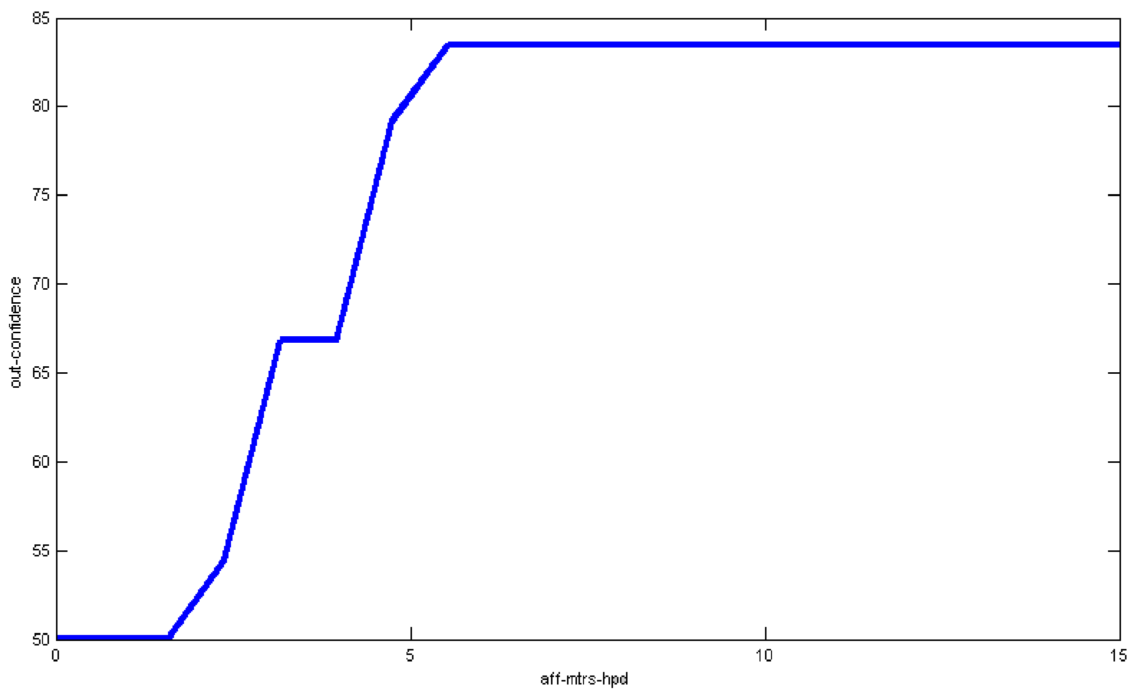


Figure 3.11 Surface for input affected meters under HPD

3.3.4. Meter Records. The last set of inputs is the indicator of the past performance of the meters in sending outage data. The rules formed using this input are fairly simple and are given in Table 3.4.

Table 3.4 Rules for input Meter Records

Meter Success Rate (%)
Membership
High
Med
Low

Output	**Weight**
Membership	
High	0.6
Med	0.6
Low	0.6

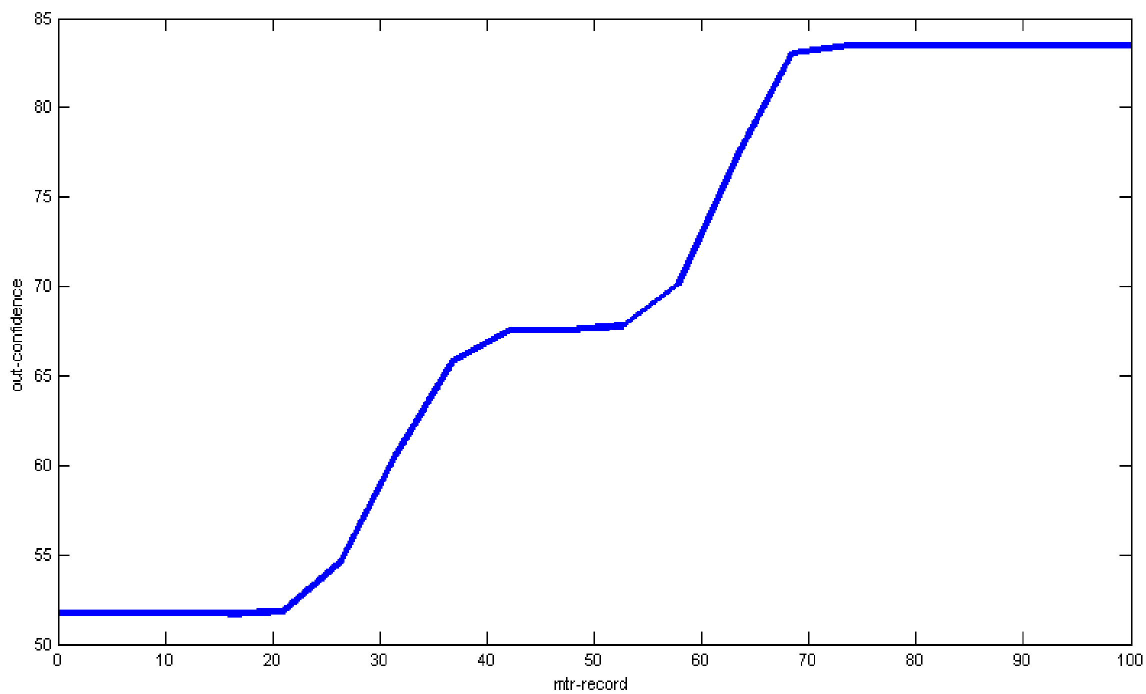


Figure 3.12 Surface for input meter records

3.4. EXAMPLE OF AMR OUTAGE DATA ANALYSIS USING FUZZY LOGIC

The following example illustrates the process of collecting outage data and extracting network information in order to form inputs for the fuzzy inference system. AMR outage data is read once every day and it includes outage flag indications and daily outage count. The highest probable device list is obtained from OAS data. The affected meters list, daily outage count, and a list of all HPDs are fed to a routine to build inputs for the fuzzy engine. For example, consider the outage data from May 24, 2010 which is summarized in Table 3.5.

Table 3.5 List of meters showing outage and outage counts from AMR data

ID_MTR_SER_NO	QTY_DAILY_OUTGE
46533803	4
17564393	1
30362477	1
43267704	1
49232261	1
52696046	1
52696055	1
52696060	1
52697118	1
94116395	1
52699530	1
52699443	1
52699428	1
52701000	1
91780273	1
52717614	5

Table 3.6 List of Highest Probable Devices from OAS data

HPD_DEV_NO
02516882007
02516881003
02516880001
280055

This outage data is processed by a routine that extracts related network information for the given affected meters' list.

Table 3.7 Affected devices list

affected devices list	
transformer no.	meter no.
2514700003	46533803
2516880001	17564393
2516880001	30362477
2516880001	43267704
2516880001	49232261
2516880001	52696046
2516880001	52696055
2516880001	52696060
2516880001	52697118
2516880001	94116395
2516881003	52699530
2516881003	52699443
2516881003	52699428
2516881003	52701000
2516881003	91780273
2516883001	52717614

Once the affected meter's list is entered, the program pulls out the transformer ID to which the meter is connected.

Table 3.8 Grouping meters according to transformer

meters affected per transformer			
transformer no.	meters	no of meters affected	total no. of customers on transformer
[2514700003]	[46533803]	[1]	[10]
[2516880001]	[1x9 double]	[9]	[14]
[2516881003]	[1x5 double]	[5]	[10]
[2516883001]	[52717614]	[1]	[8]

In Table 3.8, meters supplied by common transformer are grouped together. The table also contains a count of the number of meters affected per transformer as well as total number of customers provided by each transformer. For example, meter '46533803' is the only meter supplied by transformer '2514700003' while there are nine meters from the affected meter list that are supplied by transformer '2516880001'. The total number of customers supplied by these two transformers is ten and fourteen respectively.

Table 3.9 Grouping devices under HPD

devices affected downstream to HPD

HPD	Affected transformers under HPD	Total no. of affected devices
[2516881003]	[2516881003]	[1]
[2516880001]	[2516880001]	[1]
[280055]	[1x4 double]	[4]

In Table 3.9, the transformers from Table 3.7 that are downstream to a Highest Probable Device are grouped together and a count of total number of transformers supplied by each HPD is given in the last column. It should be noted that since '280055' is a feeder device, all four transformers are listed against the feeder ID in the Table 3.9.

Based on the example information, the inputs shown in Table 3.10 are prepared for the fuzzy engine.

Table 3.10 Inputs to the fuzzy inference system

Meter numbers	Daily outage count	Supplied by recloser? 0 = No 1 = Yes	No. of meters affected per transformer	Supplied by HPD? 0 = No 1 = Yes	No. of devices affected per HPD	Meter records (% success rate of meters based on historic data)
46533803	4	0	1	0	0	4.61
17564393	1	0	9	1	9	16.67
30362477	1	0	9	1	9	20.00
43267704	1	0	9	1	9	16.67
49232261	1	0	9	1	9	20.00
52696046	1	0	9	1	9	20.00
52696055	1	0	9	1	9	20.00
52696060	1	0	9	1	9	20.00
52697118	1	0	9	1	9	20.00
94116395	1	0	9	1	9	20.00
52699530	1	0	5	1	5	28.57
52699443	1	0	5	1	5	0.00
52699428	1	0	5	1	5	25.00
52701000	1	0	5	1	5	16.67
91780273	1	0	5	1	5	16.67
52717614	5	0	1	0	0	6.55

There are 16 meters that reported one or more outages on the day of study. Each row in Table 3.10 forms an input array for the fuzzy logic model and each array is fed one at a time. It should be noted that there are no reclosers in the network of feeder #280055. As it can be seen from Table 3.10, meters that belong to the same transformer have similar network entries in the columns containing network information although individual meter parameters such as meter records or daily outage count may not be the same.

Table 3.11 Results

Meter number	Outage reliability index (%)
46533803	29.4
17564393	75.8
30362477	75.8
43267704	75.8
49232261	75.8
52696046	75.8
52696055	75.8
52696060	75.8
52697118	75.8
94116395	75.8
52699530	75.9
52699443	75.8
52699428	75.8
52701000	75.8
91780273	75.8
52717614	27.9

The output of the fuzzy system shown in Table 3.11 gives a confidence index for every meter outage flag received from the AMR outage data. Meters supplied by a common transformer have very similar confidence indices for their reported outage flags. This is due to the similarity in the apparent outage conditions for such meters. Variations in the confidence indices, if any, are due to difference in meter records or daily outage count reported. All the meters from the above example have poor meter records, but some of the meters strongly indicate a possible group outage and hence a confidence index of approximately 75% is achieved. Had that not been the case, greater confidence indices could be expected. Another observation derived from the results above is that a meter that is part of a group of 5 meters affected on a transformer has a similar confidence index to a meter that is part of a group of 9 meters affected on a transformer when most of the other parameters are similar. This happens because if a transformer has 4 or more affected meters, then the flags from those meters belong to the high membership of input ‘meters per transformer’ and are mapped equally to the output.

The outage data for meter #17564393 is taken from Table 3.10 to graphically describe the process of mapping input conditions to the output space and the aggregation of all rules to report a crisp value as an output as shown in Figure 3.13.

Table 3.12 Inputs for graphical illustration example

Meter numbers	Daily outage count	Supplied by recloser? 0 = No 1 = Yes	No. of meters affected per transformer	Supplied by HPD? 0 = No 1 = Yes	No. of devices affected per HPD	Meter records (% success rate of meters based on historic data)
17564393	1	0	9	1	9	16.67

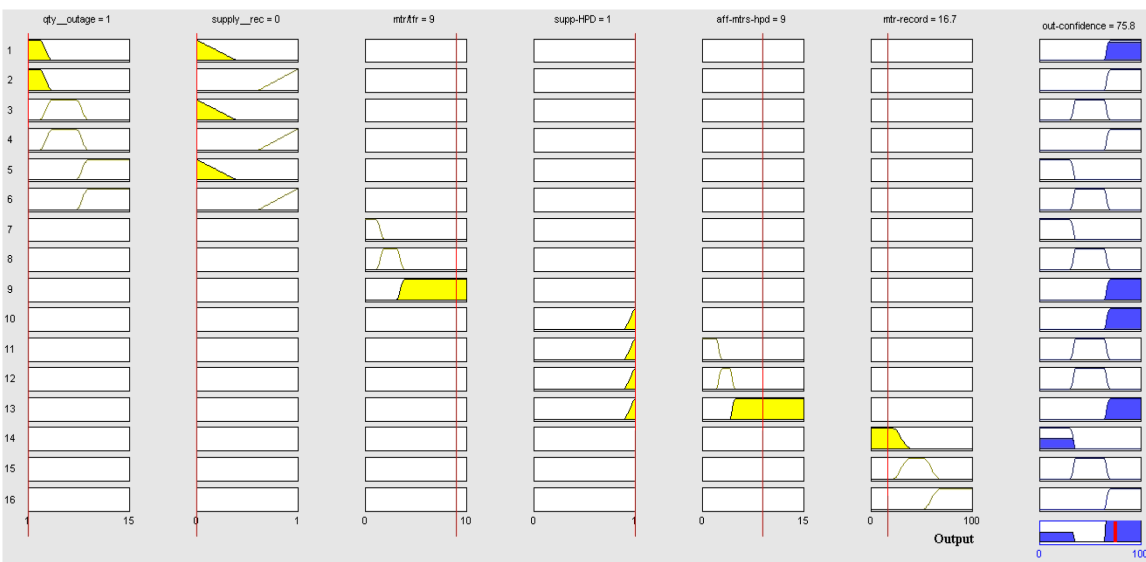


Figure 3.13 Graphical representations of rules and input to output mapping

In Figure 3.13, every column represents an input and every row is a rule that maps one or more input membership functions to the respective output membership function. In Figure 3.13, the first six rules are for inputs 1 and 2, rules 7 to 9 are for input 3, rule 10 to 13 are for inputs 4 and

5, and rules 14 to 16 are for input 6. In this example, the active rules are rule numbers 1, 9, 10, 13, and 14.

The mapping of input space to output space is done using the active rules. In rule 1, input 'qty_outage' has low membership active and input 'supply_rec' has a value zero. Rule 1 suggests that input 1 should be mapped to the high membership of output. Similarly, rule 9 maps high membership of input 3 to the high membership of output 'out-confidence'. Rules 10 and 13 suggest that the meter is part of network that is supplied by HPD, and the inputs are mapped to the high of output. The historical meter records have been poor and therefore rule 14 links the input 'mtr-record' to the low membership of the output. The output is aggregated by adding the areas of all the linked memberships. The aggregated output space is then defuzzified by finding the centroid of the entire output space which gives the crisp value for confidence index.

4. CONCLUSION

A new technique for analyzing outage flags of the automated meter reading system was developed. The proposed algorithm uses fuzzy inference techniques to model uncertainties in the outage notification data. A new approach is developed that investigates all the available outage information, and integrates this information to provide the fuzzy inference system with an intelligent data set for analysis. An estimate is drawn about the soundness of an outage notification, based upon the available outage information and prediction rules.

An information set is built for each service notification received from the automated meters. Data management routines developed earlier in this work are used to build a cogent database around the outage notification. Inputs for the probabilistic prediction model are classified to be part of focused groups or memberships. The rules for prediction of output confidence index are specifically formulated to appropriately map each of these input memberships to an output space. Each active rule shapes the outage space and contributes towards the decision making process. The output space itself is divided into three regions and based on the area mapped under each membership curve; a final crisp value is obtained.

The outage analysis model built in this work is intended to assist the utility in the outage management process. Spurious outage notifications can be filtered out and together with trouble call data, outages can be handled with high efficiency.

4.1. RECOMMENDATIONS FOR FUTURE WORK

This thesis provides a way to assist in outage location by validating AMR outages and therefore provides a tool for quicker service restoration. Once outage flags are verified and outage location is determined, the utility can attend to these confirmed outages in a timely manner. This can help the utility in reducing the restoration time and in turn improving the system reliability. System Average Interruption Duration Index (SAIDI) is one of the reliability indices that can be improved using the algorithms developed in this thesis. SAIDI is the ratio of the annual duration of interruptions sustained by customers to the total number of consumers and is specified in either minutes or hours. Consumer Average Interruption Duration Index (CAIDI) is another index which is calculated as the ratio of the total duration of interruptions to the total number of interruptions during the year. A further study can be conducted to understand the effects of utilizing AMR in outage management and the effects on system reliability.

The analysis performed in this work used outage data received over a period of two years. In this period, several meters never reported an outage. Naturally, these meters are not part of the meter conformity records that were created based on the compliance of meter's outage notification with OAS outage entries. If such a meter participates in the event of reporting outages in the future, then that meter should be added to the database with an indication of its rate of compliance.

On comparison of outage flag data with OAS data over longer period of times it was found that the meter outage data does not necessarily comply with OAS outage job records. A few possible explanations for the data conflict are that a service level work that may not show up in OAS as an outage job. For instance, a meter job performed at a customer's residence is not noted in the OAS and this may cause the outage validation algorithm to suggest that a false outage indication was reported. Other causes include temporary outages caused by a falling tree branch, operation of recloser or communication network failures not recorded in the OAS database. In order to resolve such discrepancies, the database should be corrected by going over past records of outage management works that are not part of the OAS system.

The algorithms proposed in this thesis are heavily dependent on the network orientation and device connection information. The database used for network information in this work must be constantly updated to incorporate any modifications to the physical network.

The fuzzy logic inference system was developed based on analysis of historic outage data. The pattern of outages or meter outage behavior may vary over time and the system may need to be modified with time. An advantage of fuzzy logic is that it is adaptive and can be modified easily. There are many ways of going about to improve the design of the fuzzy system based on operator's observation and expertise in order to make it highly adaptive. The output range of the currently designed fuzzy engine never operates for a full 0 to 100 % due to its inherent design. The maximum value for the output is close to 85% with the current design and rules. An operator has the choice to consider a confidence index of approximately 85% as equal or analogous to 100%. There are many uncertainties in the system that cannot be modeled. Also keeping in mind that although the meter outage obtained as a flag notification can be aided with additional outage information, probabilistically speaking there isn't sufficient information to estimate if a flag is 100% correct or not. A way to improve the sensitivity of the fuzzy systems is to include additional membership curves and minimize the areas of overlapping. Adding membership functions implies adding or modifying existing rules. Using the described methods, the designed fuzzy logic system can be made adaptive and smarter.

APPENDIX A

CODES USED FOR DATA MANAGEMENT

```
%% function to extract useful information for meter

function [trfno,pseudonode,phase,meters]=meterdata(mtrno)

%input feeder data in following format
%{[pseudo node no., dummy transformer no.]}
%example:
%F280055={  '28055',2:8;
%           'A',10:16;
%           'A1',20;
%           'B',22:26;}




%enter transformer information
%[transformer no., dummy transformer no., phase]
%transformer280055=[2090520005.00000,2,1;
%                   2090520014.00000,3,3;
%                   2090520015.00000,4,3;]


%PHASE TYPE AND ASSOCIATED NUMBER
phases={'A',1;
    'B',2;
    'C',3;
    'AB',4;
    'BC',5;
    'CA',6;
    'ABC',7;
    'UNKNOWN',9};


%ENTER METER DATA
%meter280055 = [transformer no., meter no.]
%example
%meter280055 = [2090520005.00000,30080965;
%               2090520014.00000,5586259;]


%enter customer count per transformer
%customercount=[transformer no., no. of customers]
% example
% customercount=[2090500002.00000,0;
%                2090510002.00000,0;]


k=10;           %'check' value assigned to determine exit of while loop
row=0;trfrow=0;
    while k==10
        row=row+1;
        if mtrno==meter280055(row,2)    %matching input meter no. with stored data
            k=100;
            trfrow=row;
        end
    end
trfno=meter280055(trfrow,1);    %returns transformer number

k=10;i=1;
 while k == 10
    if customercount(i,1)==trfno
        meters = customercount(i,2);
        k=100;
    end
    i=i+1;
 end

k=10;row=0;
    while k==10
        row=row+1;
        if trfno==transformer280055(row,1)
```

```
            k=100;
            trfpseudo=row;
        end
    end
trfpseudono=transformer280055(trfpseudo,2); % transformer pseudo number
ph=transformer280055(trfpseudo,3);          % corresponding number for phase connection
for i=1:8
    if ph==phases{i,2}
        phase=phases{i,1};                  %returns phase connection type
    end
end
k=10;row=0;
while k==10
    row=row+1;
    x=F280055{row,2};
    l=length(x);
    for i=1:l
        if trfpseudono==x(i)
            pseudorow=row;
            k=100;
        end
    end
end

pseudonode=F280055{pseudorow,1};            %returns pseudo node number
format long G
return

=========================================================================================

%% function for transformer data

function [pseudonode, device, ph,cust_count]=transformerdata(trfno)

% enter feeder device data as shown
%{'pseudo node number', dummy transformer no. connected, 'device no. node is connected
to'}
%example
% F280055={'28055',2:8,'280055';
%     'A',10:18,'SL83811437';
%     'A1',20,'SL83817016';
%     'B',22:26,'SL82819127';}

%enter transformer information
%[transformer no., dummy transformer no., phase]
%transformer280055=[2090520005.00000,2,1;
%                   2090520014.00000,3,3;
%                   2090520015.00000,4,3;]

phases={'A',1;
    'B',2;
    'C',3;
    'AB',4;
    'BC',5
    'CA',6
    'ABC',7
    'UNKNOWN',9};

k=10;row=0;
    while k==10
        row=row+1;
        if trfno==transformer280055(row,1)
            k=100;
            trfpseudo=row;
        end
    end
trfpseudono=transformer280055(trfpseudo,2); % transformer pseudo number
ph=transformer280055(trfpseudo,3);          % corresponding number for phase connection
for i=1:8
    if ph==phases{i,2}
        phase=phases{i,1};                  %returns phase connection type
```

```
    end
end

k=10;row=0;
while k==10
    row=row+1;
    x=F280055{row,2};
    l=length(x);
    for i=1:l
        if trfpseudono==x(i)
            pseudorow=row;
            k=100;
        end
    end
end
%finding number of customers on a transformer
%enter customer count per transformer
%customercount=[transformer no., no. of customers]
% example
% customercount=[2090500002.00000,0;
%                2090510002.00000,0;]
k=10;i=1;
 while k == 10
    if customercount(i,1)==trfno
        cust_count = customercount(i,2);
        k=100;
    end
    i=i+1;
 end

pseudonode=F280055{pseudorow,1};            %returns pseudo node number
device=F280055{pseudorow,3};                %returns device transformer is connected to
format long G
return

==========================================================================================



function [USdev,DSdev]=dev_connection(device)

%enter device connection information
%{device dummy no., downstream devices}
%example
%     devno={ 1, 1
%             1, [2,4:8,71:81];
%             2, 3;
%             8, [9,10,13,31:33,60:70];


%enter device no against device dummy no.
%{device no., device dummy no. }
% example
% refno={'280055',1;
%        'SL83811437', 2;
%        'SL83817016',3;}

    l=length(refno);
    affecteddev=0;
    check=0;
    %finding dummy no. of affected device
    for i=1:l
        check=strcmp(refno{i,1},device);
        if check == 1
            affecteddev=refno{i,2};
        end
    end

    l=length(devno(:,1));
    trackdev=affecteddev;
    k=0;    %count for no of upstream devices
```

```
    udev=0;
    %finding all devices upstream to affected device
    for i=l:-1:1
        x=devno{i,2};
        m=length(x);
        for j=1:m
            if trackdev == x(j)
%                 x;
                k=k+1;
                udev(k)=devno{i,1};
                trackdev=devno{i,1};
            end
        end

    end

    %finding all devices downstream to affected device
    trackdev=affecteddev;
    ddev=0;
    for i=1:l
        x=devno{i,1};
            if trackdev == x
                ddev=devno{i,2};
            end
    end

    %returning true device number
    if udev ~= 0
        USdev=refno(udev,1);
    end
    DSdev='none';
    if ddev ~= 0
        DSdev=refno(ddev,1);
    end


return
```

APPENDIX B

CODES FOR VALIDATION WITH OAS DATA

```
%% function to check if affected transformer is part of the HPD circuit


function [true,false]=OASmatchingTrf(trf_affected,HPD)

    trfno=HPD;
    [pseudonode, device, ph, cust_count]=transformerdata(trfno);
    USDEV1=device;                    % storing the closest upstream device to find
neighbouring devices to HPD
    [USdev,DSdev]=dev_connection(device); %cheking upstream and downstream devices
    DSdevices=DSdev;
    m=length(DSdevices);
    gen2={'null'};
    alldevices=DSdevices;
    check1=10;check2=100;
    check=strcmp('none',DSdev);
    if check==0 %proceed if device has downstream devices
        while check1~=check2
            marker=0;
            for j=1:m
                device=DSdevices{j};
                check=strcmp('none',device);
                if check==0
                    [USdev,DSdev]=dev_connection(device);
                end
                check=strcmp('none',DSdev);
                if check==0
                    %appending all the downstream devices and storing in
                    %gen2 for every DSdevice
                    for k=1:length(DSdev)
                        gen2{marker+k}=(DSdev{k});
                    end

                    marker=length(gen2);
                end
            end
            m=marker;
            check=strcmp('null',gen2{1});
            if check==1
                check1=check2;
            end
            %alldevices = entire list of DS devices
            if check==0
                alldevices={alldevices{:},gen2{:}};
            end
            DSdevices=gen2;
            gen2={'null'};
        end
    end

    cont=strcmp('none',alldevices);



%% check to determine if affected devices are part of circuit

if cont==0 %proceed if alldevices is not null
    alldevices={alldevices{:},USDEV1}; %accounts for upstream and neighboring to HPD
    flag=0;
    m=length(alldevices);
    true=[];false=[];
    l=length(trf_affected);
    for i=1:l
        trfno=trf_affected(i);
        [pseudonode, device, phase]=transformerdata(trfno);
        pgcheck=phgroup(ph,phase);%check: if same phase group

        %check to see if US device of transformer matches with alldevices
        %list
        for j=1:m
            check=strcmp(alldevices{j},device);
```

```
            if (check == 1)&&(pgcheck==1)
                flag=1;
                true=[true,trfno];
            end
        end
        if flag == 0
            false=[false,trfno];
        end
        flag=0;
    end

end
if cont==1
    alldevices=USDEV1; %accounts for neighboring devices to HPD only
    flag=0;
    true=[];false=[];

    m=1;
    l=length(trf_affected);
    for i=1:l
        trfno=trf_affected(i);
        [pseudonode, device, phase]=transformerdata(trfno);
        pgcheck=phgroup(ph,phase);

        for j=1:m
            check=strcmp(alldevices,device);
            if (check == 1)&&(pgcheck==1)
                true=[true,trfno];
                flag=1;
            end
        end
        if flag == 0
            false=[false,trfno];
        end
        flag=0;
    end
end
%%
return

==========================================================================================

%% function to check if affected devices are part of the HPD (fuse/switch) circuit


function [true,false]=OASmatchingSw(dev_affected,HPD)


    device=HPD;
    [USdev,DSdev]=dev_connection(device);
    USDEV1=dev_affected;
    DSdevices=DSdev;
    m=length(DSdevices);
    gen2={'null'};
    alldevices=DSdevices;
    check1=10;check2=100;
    check=strcmp('none',DSdev);
    if check==0
        while check1~=check2
            marker=0;
            for j=1:m
                device=DSdevices{j};
                check=strcmp('none',device);
                if check==0
                    [USdev,DSdev]=dev_connection(device);

                end
                check=strcmp('none',DSdev);
                if check==0
                    for k=1:length(DSdev)
                        gen2{marker+k}=(DSdev{k});
```

```
                    end

                    marker=length(gen2);
                end
            end
            m=marker;
            check=strcmp('null',gen2{1});
            if check==1
                check1=check2;
            end
            if check==0
                alldevices={alldevices{:},gen2{:}};
            end
            DSdevices=gen2;
            gen2={'null'};
        end
    end


    cont=strcmp('none',alldevices);


%% check to determine if affected devices are part of circuit

if cont==0
    alldevices={alldevices{:},USDEV1{:}};
    flag=0;
    true=[];false=[];
    m=length(alldevices);

    l=length(dev_affected);
    for i=1:l
        trfno=dev_affected(i);
        [pseudonode, device, phase]=transformerdata(trfno);
        pgcheck=1;

        for j=1:m
            check=strcmp(alldevices{j},device);
            if (check == 1)&&(pgcheck==1)
                true=[true,trfno];
                flag=1;
            end
        end
        if flag == 0
            false=[false,trfno];
        end
        flag=0;
    end
end

if cont==1
    alldevices=USDEV1;
    flag=0;
    true=[];false=[];
    m=1;
    l=length(dev_affected);
    for i=1:l
        trfno=dev_affected(i);
        [pseudonode, device, phase]=transformerdata(trfno);
        pgcheck=1;

        for j=1:m
            check=strcmp(alldevices,device);
            if (check == 1)&&(pgcheck==1)
                true=[true,trfno];
                flag=1;
            end
        end
        if flag == 0
            false=[false,trfno];
        end
```

```
        flag=0;
    end
end

%%

return

==========================================================================================

%Function to check if devices belong to circuit of HPD (transformer)

function [TRUE]= meter_rel_check_tfr(dev_affected, HPD)

%% eliminate redundant entries in affected devices list
z=length(dev_affected);
i=1;
while i<=z;
    var=dev_affected(i);
    j=i+1;
    while j <= z

        if var==dev_affected(j)
           dev_affected(j)=[];
           j=j-1;
        end
        z=length(dev_affected);
        j=j+1;
    end
    i=i+1;
end



%% eliminate redundant entries in HPD
z=length(HPD);

i=1;
while i<=z;
    var=HPD(i);
    j=i+1;
    while j <= z

        if var==HPD(j)
           HPD(j)=[];
           j=j-1;
        end
        z=length(HPD);
        j=j+1;
    end
    i=i+1;
end

%%
TRUE=[];
%% HPD = transformer
l=length(HPD);
for i=1:l

    [true,false]=OASmatchingTrf(dev_affected,HPD(i));

    TRUE=[TRUE,true];

end

%% eliminate redundant entries in matched outage entries
z=length(TRUE);

i=1;
while i<=z;
```

```
    var=TRUE(i);
    j=i+1;
    while j <= z

        if var==TRUE(j)
           TRUE(j)=[];
           j=j-1;
        end
        z=length(TRUE);
        j=j+1;
    end
    i=i+1;
end

return

==========================================================================================

%Function to check if devices belong to circuit of HPD (fuse/switch)
%HPD entries are one at a time

function [true,false]= meter_rel_check_sw(dev_affected, HPD)


%% eliminate redundant entries in affected devices list
z=length(dev_affected);
i=1;
while i<=z;
    var=dev_affected(i);
    j=i+1;
    while j <= z

        if var==dev_affected(j)
           dev_affected(j)=[];
           j=j-1;
        end
        z=length(dev_affected);
        j=j+1;
    end
    i=i+1;
end


%% HPD = FUSE/SWITCH
[true,false]=OASmatchingSw(dev_affected,HPD);

return

==========================================================================================

clear all;clc
%% this data set includes ONLY THOSE devices that had information about their network
connection
%example of data
TME_MTR_XFMR=[2516880006.00000,52699412,1,39859;2515540016.00000,52705013,1,39860;2516880
006.00000,52699412,2,39860;];
OAS_ORDER_DETAIL={2090520012.00000,39855,1327;2515545020.00000,39856,221;2516880003.00000
,39856,216;2516881015.00000,39856,221;};


events=length(TME_MTR_XFMR);
orders=length(OAS_ORDER_DETAIL);
track1=1;start=1;track2=1;
METER=[];

while (track1 <= events) && (track2 <= orders)
    %% grouping affected meters and transformers list for a given date
    date1=TME_MTR_XFMR(track1,4);
    start=track1;
    while (track1 <= events)&&(date1 == TME_MTR_XFMR(track1,4))
        track1=track1+1;
```

```
    end
    stop=track1-1;

    aff_dev=TME_MTR_XFMR(start:stop,1);
    aff_meter=TME_MTR_XFMR(start:stop,2);
    outage_qty=TME_MTR_XFMR(start:stop,3);
    dates=TME_MTR_XFMR(start:stop,4);
    device_list=[aff_dev,aff_meter];

    %% eliminate redundant entries in affected meters and device list
    z=length(aff_meter);
    i=1;
    while i<=z;
        var=aff_meter(i);
        j=i+1;
        while j <= z

            if var==aff_meter(j)
               aff_meter(j)=[];
               outage_qty(j)=[];
               device_list(j,:)=[];
               j=j-1;
            end
            z=length(aff_meter);
            j=j+1;
        end
        i=i+1;
    end

%%



%% grouping HPD for that date and a day later
    date2= OAS_ORDER_DETAIL{track2,2};

    while (track2 <= orders) && (date2 < date1) %checking for the same date as date1
        track2=track2+1;
        date2= OAS_ORDER_DETAIL{track2,2};
        marker=track2;
    end

    start=[];stop=[];HPD=[];
    if date2 == date1
        start=track2;
        while (track2 <= orders)&&(date2 == OAS_ORDER_DETAIL{track2,2})
            track2=track2+1;
        end
        stop=track2-1;
        HPD=OAS_ORDER_DETAIL(start:stop,1);
    end

    date2= OAS_ORDER_DETAIL{track2,2};
    if (date2 == date1+1)
        if isempty(start)
            start=track2;
        end
        while (track2 <= orders)&&(date2 == OAS_ORDER_DETAIL{track2,2})
            track2=track2+1;
        end
        stop=track2-1;
        HPD=OAS_ORDER_DETAIL(start:stop,1);
    end


%% verifying relation of entries from outage data and OAS records

    L=length(HPD);
    HPDtf=[];HPDsw={};
    i=1;IStrf=0;
    TRUE=[];feeder=0;
```

```
    for count=1:L
        DEV_NO=HPD{count};
        if DEV_NO == 280055
            feeder = 1;
            TRUE = aff_dev;
        end

        if DEV_NO ~= 280055
            DEV_TYPE=ischar(DEV_NO);
            if (DEV_TYPE==0)
                HPDtf=[HPDtf,DEV_NO];
                IStrf=1;
            end

            if (ischar(DEV_NO))
                HPDsw=DEV_NO;
                [true,false] = meter_rel_check_sw(aff_dev, HPDsw);
                TRUE=[TRUE,true];
            end
        end
    end

    if (IStrf == 1) && (feeder == 0)
        true=meter_rel_check_tfr(aff_dev,HPDtf);
        TRUE=[TRUE,true];
    end


    l=length(TRUE);
    L = length(aff_meter);
    for i=1:L
        meter=aff_meter(i);
        trf=device_list(i,1);
        correct_tr=0;
        for j=1:l
            if trf==TRUE(j)
                correct_tr=1;
            end
        end
        qty_outage=outage_qty(i);
        METER=[METER;meter,correct_tr,qty_outage,date1,date2];
    end



end

dailyresult=METER;

z=length(METER);
METER(:,6)=1;
i=1;
while i<=z;
    var=METER(i,1);
    j=i+1;
    while j <= z
        if var==METER(j,1)
            METER(i,2)=METER(i,2)+METER(j,2);
            METER(i,3)=METER(i,3)+METER(j,3);
            METER(i,6)=METER(i,6)+METER(j,6);
            METER(j,:)=[];
            j=j-1;
        end
        z=length(METER);
        j=j+1;
    end
    i=i+1;
end
METER(:,4:5)=[];
```

APPENDIX C

CODE FOR GENERATING INPUTS FOR FUZZY INFERENCE SYSTEM

```
% outagevalidation
% Program to generate inputs for fuzzy logic

format long
disp('enter affected meter list');
aff_meter=input('');

l=length(aff_meter(:,1));
otg_qty = aff_meter(:,2);
trf_no=[];
for i=1:l
    trf_no(i)=meterdata(aff_meter(i,1));
end
aff_devs=[trf_no',aff_meter(:,1)];
disp('affected devices list')   % list of transformers for respective meters
disp(aff_devs)

%%
z=length(trf_no);
i=1;
while i<=z;
    var=trf_no(i);
    j=i+1;
    Meter=aff_meter(i,1);
    while j <= z
        if var==trf_no(j)
            Meter=[Meter,aff_meter(j,1)];     %grouping meters under same transformer
            trf_no(j)=[];
            aff_meter(j,:)=[];
            j=j-1;
        end
        z=length(trf_no);
        j=j+1;

    end
    [~, ~, phase,custcnt]=transformerdata(trf_no(i));
    grp_meters(i,:)={trf_no(i),Meter,length(Meter),custcnt};
    aff_met_cnt(i)=length(Meter);
    i=i+1;
end
disp('meters affected per transformer')     %meters grouped under respective transformer
disp(grp_meters)                            %to find out  meters/transformer count

[~,b]=max(aff_met_cnt);
ref_tfr=grp_meters{b,1};

%% enter HPD
disp('enter Highest Probable Device list');
HPD=input('');

% eliminating redundancy in HPD
z=length(HPD);
i=1;
while i<=z;
    var=HPD{i};
    j=i+1;
    while j <= z

        if strcmp(var,HPD(j))
            HPD(j)=[];
            j=j-1;
        end
        z=length(HPD);
        j=j+1;

    end
    i=i+1;
end

%% grouping meters and escalation
%outages traced in network to find out if meters affected under HPD
```

```
[~,L]=size(HPD);
i=1;IStrf=0;
TRUE=[];feeder=0;
for count=1:L

    DEV_NO=HPD{count};
    DEV_TYPE=ischar(DEV_NO);
    if DEV_NO == 280055
        TRUE = trf_no;
        dev_matching(i,:)={DEV_NO,TRUE,0};
        i=i+1;
    end

    if DEV_NO ~= 280055
        if (DEV_TYPE==0)
            HPDtf=DEV_NO;
            true=meter_rel_check_tfr(trf_no,HPDtf);
            dev_matching(i,:)={HPDtf,true,length(true)};
            i=i+1;
        end

        if (DEV_TYPE==1)
            HPDsw=DEV_NO;
            [true,false] = meter_rel_check_sw(trf_no, HPDsw);
            dev_matching(i,:)={HPDsw,true,length(true)};
            i=i+1;
        end
    end

end

[z,k]=size(dev_matching);
for i=1:z
    groupcount(i)=(dev_matching{i,3});
end
disp('devices affected downstream to HPD');
disp(dev_matching)

[a,b]=max(groupcount);
refdev=dev_matching{b,1};   %is the device with most affected trfs downstream



%% Input to fuzzy
z=length(otg_qty);

for i=1:z
    qty_outage = otg_qty(i);    %INPUT #1
    supply_rec = 0;     %INPUT #2
    mtr_tfr = (grp_meters{i,3})/(grp_meters{i,4})*10;   %INPUT #3
    supp_hpd = 0;      %=1 if supplied by HPD, =0 otherwise

    aff_mtr_hpd=0;
    mtr_rec = 20;
end
```

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VITA

Prasad Shinde was born on March 25, 1987 in Mumbai, India. He received his Bachelor of Technology degree in Electrical Engineering in 2008 from College of Engineering Pune, India. From August 2008 to July 2010 he worked at Reliance Infrastructure, India as an Assistant Manager. He joined Missouri University of Science and Technology to pursue his Master of Science degree in Electrical Engineering. His areas of interests include power systems operation, computational methods in power systems, and power converter design and modeling. He received his M.S in Electrical Engineering degree in May 2012.