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Testing of Advanced Metering Infrastructure Systems: Evaluation Process and Analysis

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Abstract

The Advanced Metering Infrastructure comprises a collection of smart meters installed in residential and commercial areas, which gather information on energy consumption and billing from consumer meters and transmit it to the electricity supplier through a communication channel. This infrastructure includes Smart Meters, a communication software platform, a data management system, and a prepaid billing system. This network setup facilitates two-way communication, enabling the efficient monitoring, seamless collection, and analysis of energy data. Electro-mechanical meters are deemed inefficient due to their inefficiency in metering accuracy, susceptibility to theft through direct hooking, and inadequate collection methods. To mitigate these Aggregate Technical & Commercial (AT & C) losses, the Indian Government has introduced the Revamped Distribution Sector Scheme (RDSS). Under this scheme, financial assistance is provided to DISCOMS for enhancing the Prepaid Smart Metering system subject to meeting specific criteria and attaining a minimum benchmark in reforms. This paper aims to present a detailed analysis and evaluation of the testing process for the Smart Meter within the AMI system.

Keywords: AMI, AT&C Losses, RDSS, Smart Meter

1. Introduction

The Smart Grid is a modern and advanced electrical system that incorporates computational intelligence in a unified manner throughout the processes of electricity generation, transmission, substations, distribution, and consumption. Its ultimate goal is to establish secure, sustainable and efficient smart technologies over the complete range of the energy system, spanning from the production to the final destinations where electricity is consumed. It will require several decades for the complete realization of a smart grid, as it is a gradual and evolutionary process. Advanced Metering Infrastructure (AMI) plays a crucial role in the smart grid as it facilitates the exchange of data and signals between consumer smart meters and the power utilities supplier. It offers advanced features like gathering metering data for billing, facilitating two-way communication, enabling demand response, managing load, detecting tampering and handling outages[1].

Smart meters give automatic reading capability to utility companies and provide customers with the convenience of prepaid recharge options. This eliminates the need for expenses related to vehicles, training, health insurance, and other overhead costs associated with manual meter readings. Furthermore, the streamlined read-to-pay process reduces the time taken and improves the utility's cash flow, resulting in a significant advantage. Additionally, customers no longer have to worry about meter readers entering their premises, as this concern is eliminated. It is an environmentally friendly system as it allows for demand response, which can result in reduced emissions and carbon footprint. Moreover, it promotes enhanced energy efficiency as studies have demonstrated that providing consumers with information feedback alone can lead to a decrease in energy consumption[2].

The statistical data gathered from Indian power utilities in recent years indicates that the revenue gap, AT&C losses, and Billing Efficiency have not reached the desired level of

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effectiveness in the energy system. As there is progress being made in these areas by advanced metering technology, we expect a transition to an efficient metering environment. The data percentage for AT&C losses and Billing Efficiency for Indian distribution utilities from FY 2016-17 to FY 2021-22 is shown in Figure 1 and Figure 2 respectively[3].

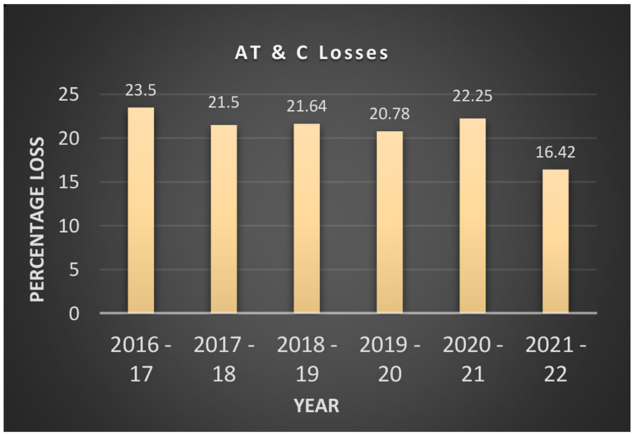

Figure 1. AT & C loss of Indian power distribution utilities.

To establish the AMI system and to fulfil its requirement, the Ministry of Power implemented the Revamped Distribution Sector Scheme (RDSS) with a budget of Rs. 3,03,758 crores. Under this Scheme, the Government provides financial assistance to DISCOMs. Its main objective is to bring down the AT&C losses to pan-India levels of 12-15% and eliminate the gap between Average Cost of Supply (ACS) and Average Revenue Realised (ARR) by the year 2024-25[4]. As part of the RDSS Project, the Ministry of Power has sanctioned 19.79 crore meters for different utilities throughout India. As of January 2024, the state utilities have successfully installed approximately 26 lakhs of these meters[5].

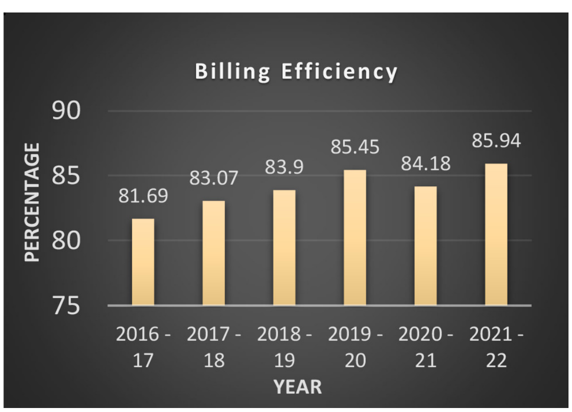

Figure 2. Billing Efficiency of Indian power distribution utilities.

Before implementation of any extensive system, Testing is of utmost importance as it offers valuable perspectives on the functioning and overall state of a system. The RDSS Scheme has implemented initiatives to evaluate the efficiency of communication performance to observe the tangible advantages of AMI. It evaluates the performance of the smart Meter, billing system and software platforms. These testing results have caught several obstacles including data transmitting problems with smart meters, complications in reconnecting after recharging, automatic disconnection when the balance is reduced to negative and the need to select the appropriate communication technology.

This paper primarily centres around providing a detailed analysis of the testing results obtained from the AMI system. and presents the failure and challenges obtained through these results. The manuscript is structured into five distinct sections. Within Section 2, an in-depth analysis is presented, encompassing the entirety of the AMI system's components and their functioning. Section 3 delves into the testing process and presents the obtained results. Section 4 focuses on the analysis of failures in the testing results. Lastly, Section 5 serves as the conclusion of the paper, summarizing the significant findings and insights derived from the testing results.

2. Advanced Metering Infrastructure System

The AMI system is comprised of Smart meters, software platforms and a prepaid billing system. The software platforms employed in this procedure are the Head-end system and Meter data management which manages the energy data collection, and validation. Different communication technologies are utilized for transferring data between the HES and consumer Smart Meter, depending on the type of smart meter being used. After gathering real-time data from a vast array of smart meters, the HES analyzes the information before transmitting it to the Meter Data Management (MDM) system.

HES is capable of communicating with multiple meters simultaneously using wired or wireless communication technology, whereas MDM establishes a single line connection with HES and efficiently transmits the data to the utility for accurate energy measurement and billing[6]. The incorporation of these Hardware and Software components facilitates a seamless two-way communication of information between smart meters and utility companies. The hardware and software elements of AMI and their detailed functionalities are discussed in this section.

2.1 Smart Meters

A smart meter has various built-in sensors and control devices, which are backed by a dedicated communication infrastructure. The data collected by smart meters comprises the meter's distinct identifier, the timestamp of the data, electricity consumption values, and other relevant information. The utility can make use of the data collected from smart meters to enable real-time pricing. This enables companies to establish restrictions on the maximum electricity usage and encourage users to decrease their demands during periods of high load. Moreover, the system operator can remotely disconnect or reconnect the electricity supply to customers through suitable mechanisms. This optimization of power flows is based on the information received from the demand side[7].

Smart meters offer benefits not only to utility companies but also to customers who can enjoy a range of advantages. These encompass the convenience of estimating bills using collected data, receiving precise and timely billing, and gaining enhanced awareness of energy consumption. Smart meters can utilize various communication technologies, such as Cellular networks, RF (Radio Frequency), or PLC (Power Line Communication), depending on the specific implementation. This communication facilitates prompt and efficient transmission of data between HES and Meters, ensuring privacy and accuracy.

2.2 Head End System (HES)

The Head End System serves as a vital software platform within AMI. It functions as a mediator between the consumer meter and the MDM software application. HES is responsible for storing and analyzing real-time data and events captured from smart meters. HES functions as a temporary database where the unprocessed meter data can be stored for a specified period before being transferred to the meter data management system. In the event of a communication link failure, it also initiates retry attempts to establish communication with meters.

The core aim of HES is to effortlessly gather meter data without any human intervention and analyze the parameters acquired from the meters. HES retrieves data from the smart meter at predetermined intervals, which can be adjusted, as well as on request. Also, HES supports consumers by providing them with the necessary information to make informed decisions and access enhanced services[8]. The role of HES includes the following functions:

- Acquiring meter data upon request and at user-selected intervals.
- Enabling two-way communication with the meter.
- Sending signals to connect or disconnect switches located at endpoints, such as the meter.
- Maintaining an audit trail and logging events and alarms.
- Storing raw data for a specified duration.
- Enabling the customization of smart meter settings.
- Providing information on the status and history of communication devices.
- Offering both critical and non-critical reporting functionality.
- Maintain time synchronization with DCU/meter[9].

2.3 Meter Data Management Systems (MDMS)

The primary function of this system is to serve as a centralized storage for data. The Meter Data Management (MDM) system is equipped with the ability to import data in specified formats, whether it is raw or already validated. Furthermore, it can export the processed and validated data to different systems, sources, and services in the agreed format. It can categorize, arrange in order of importance, sort out, and dispatch alerts and notifications generated by the system to prearranged email addresses, mobile text messages to phone numbers/SMS, and customer care services[9]. The basic features of the MDM system include:

- Maintaining information and records concerning the present installed meter location, consumer information, consumer account number, meter ID, meter type, and meter configuration.
- Offer end-to-end support for device lifecycle management, ensuring a seamless experience from device registration, installation, provisioning, and ongoing operations and maintenance, right through to the decommissioning process.
- Possess the capability to store data for at least 5 years or even longer through archiving.
- Capacity to capture and record data exceptions, issues, and malfunctions enables the automated generation of service requests.
- Deal with distinct metering arrangements, such as net metering or the coexistence of multiple meters within a single location.

2.4 Communication Technology

Wireless technology, such as cellular and RF technology, is commonly utilized in AMI systems for communication purposes between HES and Meters. These communication options provide several benefits compared to wired technology, including cost-effectiveness and the ability to establish connections in remote locations. However, it is crucial to carefully evaluate various factors such as geographical topography, technical and operational requirements, and cost to determine the most appropriate communication method for a particular scenario. It is worth noting that wired connections are generally less susceptible to interference issues[10].

2.5 PLC Communication

Power line communication, also known as PLC, is a wired communication technology that utilizes the existing power transmission lines to transmit collected data from the meter to the DCU. DCU transfers collected data to HES. One notable advantage of PLC is its lower initial cost, as it makes use of the already established power line infrastructure. However, it is important to acknowledge a significant drawback of this communication method, which is the noise generated by power electronics components in the channel, leading to slow data transmission. Moreover, data distortion can occur around transformers, which necessitates the implementation of alternative communication techniques to overcome these challenges[10].

2.6 RF Technology

In this particular technological system, Measurement data from the end consumers is collected by the smart meter, which is then transmitted wirelessly via radio frequency (operating at 865-868MHz as per allowed licence-free frequency range in India) to a data concentrator unit. The DCU establishes connectivity with around 50 to 150 smart meters located nearby, usually utilizing a mesh topology. Mesh technology refers to the interconnection of devices, resembling a spider's web, to maximize coverage and bandwidth utilization. DCU establishes communication with HES through the utilization of a cellular network. Nevertheless, in the event of any issues with the DCU, it can lead to communication disruptions for all the smart meters linked to it via HES[11].

2.7 Cellular Technology

By using cellular technology, The HES facilitates direct wireless communication with the smart meters, removing the need for an intermediary device like DCU. Data transmission from the smart meters to the HES is accomplished through cellular networks like 2G, 3G, 4G, or GPRS. Furthermore, the utilization of 5G and NBIOT has become increasingly prevalent. HES extract the data from the meter and initiates commands directly to the meters through this direct communication.

Although all three types of communication offer the advantage of two-way communication, they differ in terms of performance, implementation cost, data transfer speed, and accuracy. Depending on the specific requirements and location, a suitable communication technology is chosen to ensure efficient data transfer between the Head End System (HES) and the smart meter.

To standardize the data exchange, meter reading, tariff and load and control, The India Companion Specification (ICS) has been developed by the Bureau of Indian Standards (BIS) and made available to the public[12-14]. Table 1 summarises the Indian standards for smart meters.

Table 1. Indian standards for smart meter

Standard	Description
IS 15959-2, 2016	Companion specification: Part 2 focuses on data exchange for electricity meter reading, tariff, and load control.
IS 15959-3, 2017	Companion specification: Part 3 (Transformer Operated KWh and KVarh, Class 0.2 S, 0.5 S and 1.0 S) standardize Data exchange for electricity meter reading, tariff, and load control.
IS 16444-1, 2015	Specification for AC static direct connected watthour smart meter class 1 and 2.
IS 16444-2, 2017	Part 2 of the specification covers AC static transformer operated watthour and var-hour smart meters (class 0.2 S, 0.5 S, and 1.0 S)

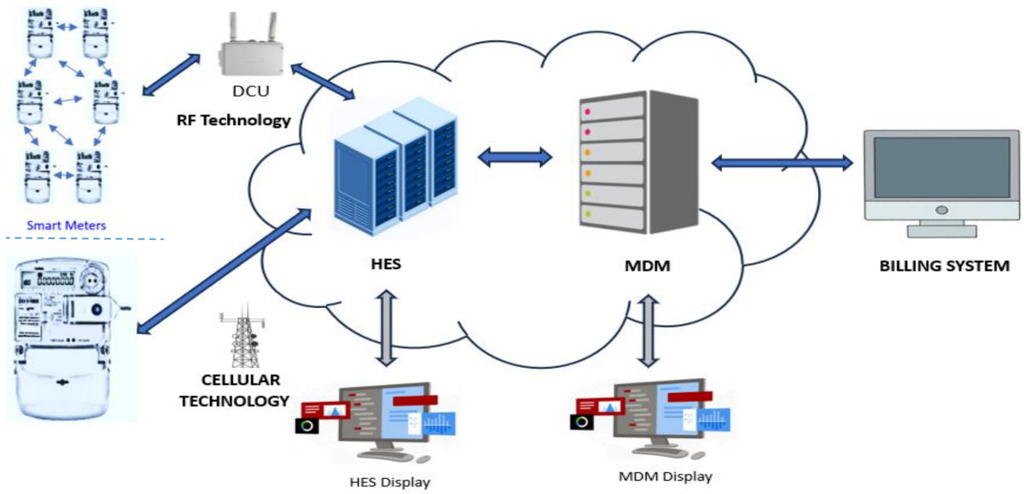

Figure 3. Advanced metering infrastructure system.

3. Testing Process of AMI System

The testing process is a sequence of specific actions performed to ensure that the software and hardware quality objectives are met as per requirement. To assess the performance level, it is crucial to carry out preliminary testing with a limited quantity for any extensive system development, such as the AMI system. To gain authorization for implementing meters in the field of AMISPs, their AMI system's functionalities must comply with the performance level specified in the documents of RFE. Given this, the RDSS project was implemented by the Ministry of Power to enforce mandatory testing for all AMISPs. The development of this testing procedure was established per the guideline to assess the efficiency of meter performance in terms of accurate billing, remote connection and disconnection, prepaid recharging, tamper and event detection, as well as meter data collection.

In this testing process, AMISPs are required to demonstrate their system by utilizing a minimum of 20 smart meters with at least 5 meters from two different makes, as per the RFE's requirement. Normally, AMISPs only integrate one specific make of smart meter in the field. However, the Applicant must also guarantee the installation and integration of at least another one made of smart meters to fulfil the Empanelment requirements and demonstrate their capabilities as per the RFE (Request for Empanelment) document[15].

This testing procedure spans over one week and includes daily test procedures from day 2 to day 6. Additionally, there is a regular test procedure that can be completed within a week as a single-time testing procedure. Furthermore, there are scheduled test procedures specifically designed for billing tests.

On the first day of testing, before commencing significant test cases, AMISPs should time synchronize their HES and MDM system with the smart meter to avoid problems such as block data loss and to guarantee the timely transmission of data and alerts. Also, AMISPs are advised to reset the maximum demand to reset previous demand data.

Figure 4. Test bed set-up.

Regular test cases are test cases that AMISPs can be able to do on any day of that particular week. These test cases consist of

- Remote connect/disconnect.
- Tamper detection.
- Firmware upgrade.
- Recharge success alert.
- Collection of interval load profile.
- Meter disconnection and connection after balance calculation.

Due to the limited duration provided for testing, Certain test cases apply to only five out of the 20 meters, specifically those that are randomly chosen. These particular test cases include remote connection and disconnection, recharge success alert, and tamper detection. This testing process exclusively utilizes a one-scheduled test procedure to evaluate billing efficiency usually conducted on the 5th day of testing. Nevertheless, the daily monitoring of balance consumption is conducted to obtain detailed information regarding energy consumption and recharge history.

The Smart meter can transmit energy consumption data to the Head End System (HES) every 15 or 30 minutes. As per the standard, a total of 96 or 48 blocks (4 or 2 blocks per hour * 24 hours) of data are expected from a single meter in a single day. These block counts and received time are verified daily from day 2 to day 6 during the testing phase. Also, in this period of day 2 to day 6, several test cases are conducted daily. These include the verification of

- Instantaneous reading which has instant meter values such as voltage, current etc.
- Nameplate with firmware version, meter rating
- Daily load profile which contains information on energy consumed in a single day
- Captured event and alert at HES and MDM.

In this testing process, almost half of the test cases are verified based on the reporting time of data or events captured. These meter parameters and the required performance level on reporting time are mentioned below in Figure 5.

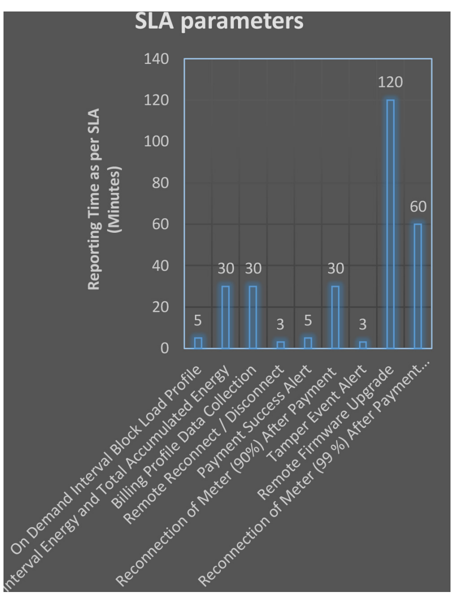

Figure 5. AMI Testing SLA Parameter.

4. Analysis of AMI System Testing Result

In this section, a comprehensive analysis of the testing results is conducted, incorporating detailed statistics from the testing conducted at CPRI Bangalore and Bhopal laboratories. The primary cause of failure in the AMI system can be attributed to the time-dependent nature of the testing procedures. These specific test procedures are referred to as Service Level Agreements Parameters in the document provided by RFE. The subsequent sections will elaborate on the test requirements and the expected performance levels.

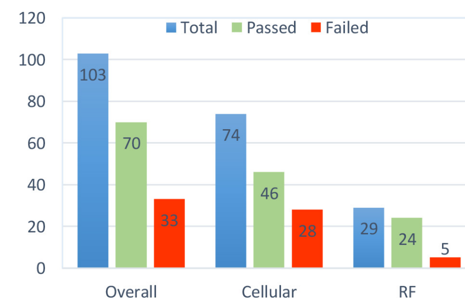

Figure 6. Statistics of AMISP testing at the laboratory.

Figure 6 represents statistics of AMISPs tested at the laboratory as of January 2024. Out of the 103 AMISPs that were tested, 74 of them relied on cellular communication, whereas the remaining 29 were dependent on RF communication. Among these 103 AMISPs, a total of 33 AMISPs (32.038%) failed to meet the validation process requirements, encompassing both RF and cellular technologies. Specifically, within the cellular technology category, the non-compliance rate was 37.83% (28 out of 74), whereas in the RF technology category, the non-compliance rate stood at 17.24% (5 out of 29).

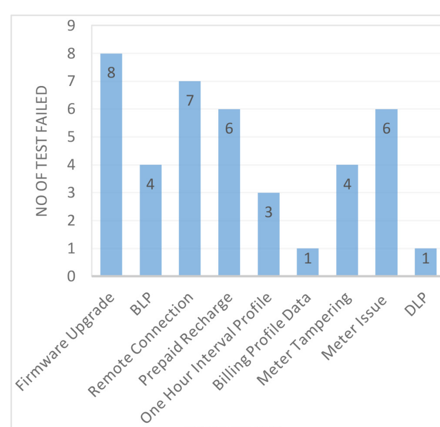

Figure 7. Failure statistics.

The failures mentioned above in Figure 7 do not imply failure happened due to that the processes are incomplete. They have been completed, but they were not reported within the required timeframe of SLA.

4.1 Firmware Upgrade Failure

Firmware acts as a bridge between the hardware and software components of a system, enabling the hardware to communicate with the operating system and applications. Unlike software, Firmware is not intended for frequent modification or updates, and it is usually stored in non-volatile memory. As per SLA, the firmware update should be completed within a maximum of 2 hours. If the update takes longer than 2 hours, the testing process will be deemed unsuccessful. Compared to other testing processes, a significant number of 8 out of 103 AMISPs failed during this testing process. Out of these 8, 7 were specifically related to cellular-based AMISPs. Firmware details are usually verified in nameplate details in HES.

4.2 Load Profile Failure

HES gathers energy usage information at regular intervals of either 15 or 30 minutes, as well as the total consumption every 24 hours, from the smart meter. This data proves highly valuable for utilities as it enables them to notify customers about the increase in their energy consumption during specific periods. If the meter fails to push load profile data to HES within 30 minutes past midnight, the test case is considered as failed. As a result of this communication failure, 5 AMISPs were unsuccessful. Among these 5, 4 failed due to Block Load Profile (BLP) and 1 was due to Daily Load Profile (DLP).

4.3 Meter Tampering Alert Failure

Unlike conventional electro-mechanical meters, the smart meter has the capability of finding meter tampering such as earth leakage, current reversal and energy theft. If the meter fails to send the alert to the utilities within 3 minutes by communicating through the HES and MDM, it will be considered a failure. Usually, tamper ID is used by utilities to alert the consumers. This testing process highlights the significance of detection. 4 out of 103 AMISPs failed to send the alert within the specified timeframe.

4.4 Remote Meter Disconnection and Reconnection Failure

If any instances of Meter Tampering, Fire accident or any other unnecessary activities are detected, utilities can remotely disconnect and reconnect services. In this testing process, the meter should be reconnected or disconnected within 3 minutes, based on the command sent by the utilities to the HES. If the meter does not respond to this command, its communication will be deemed as unsuccessful as per SLA. 7 out of 103 AMISPs failed to meet these requirements.

4.5 Prepaid Recharge Failure

Before initiating this testing process, we manually ensured that the meter would be disconnected upon reaching a negative balance by recharging a smaller amount before the day. During this procedure, as the meter is recharged, it will acquire a positive balance. Once the recharge is completed, the Meter Data Management (MDM) system calculates the balance (positive) and triggers a reconnect command to the meter via the Head End System (HES). Consequently, the smart meter reconnects and updates its connection status in both the HES and MDM systems. In accordance with the requirements, the consumer receives an acknowledgement for the recharge via Email, SMS or Mobile Application. The verification process involves checking the time it takes for the payment trigger to send the payment success alert, as well as the time it takes for the payment success to meter reconnection. It is important that the meter is reconnected within 30 minutes after a successful recharge, and a notification should be sent to the customer within 5 minutes. 6 AMISPs out of 103 failed to meet these criteria.

4.6 One-Hour BLP Failure

If utilities wish to authenticate the energy consumption data from any meter for the previous hour, the utility can command the meter accordingly. The meter is required to transmit the data to the utilities via HES and MDM within a maximum timeframe of 5 minutes, as specified by the SLA. This requirement was not met by 03 AMISPs out of 103.

4.7 Billing Profile Data

Since the meters are prepaid, billing is not utilized for payment purposes; rather, it serves solely for the verification of balance, tariff and consumption details. In practice, Utility schedule and Trigger command for billing system and send to MDM/HES for collection of Monthly billing Data. As per the schedule, MDM is responsible for sending a request to the Smart Meter. In case the Meter data is not collected within the specified time, there should be provision for retrial. HES is then responsible for decrypting and validating the collected data, which is then sent to MDM. MDM, in turn, sends the required parameter to the Billing system for Monthly Bill calculation. Due to the limited duration of the testing period, the billing process is scheduled to trigger weekly billing data at midnight on the sixth day of the week. The meter is required to transmit data within 30 minutes of the scheduled time. 1 AMISPs failed to receive the billing profile within the specified timeframe.

4.8 Meter Issue

Meter issues are distinct from other failures in the testing process due to their association with malfunctioning physical components. AMISPs often encounter significant meter issues such as unknown meter relay connect/ disconnect, unresponsiveness to commands, and failure to power up. Despite undergoing both a type test and routine test in accordance with the standard, smart meters may still encounter failures during communication tests. These failures can be attributed to physical meter issues arising from insufficient maintenance and transportation.

5. Conclusion

In this paper, the testing process of advanced metering infrastructure and result analysis of tests performed in the laboratory are discussed. The study of failures in Advanced Metering Infrastructure (AMI) is a fundamental discipline that explores the causes and impacts of AMI system failures. Understanding and rectifying these problems can result in enhanced precision and effectiveness, benefiting both consumers and utility companies. In terms of future progress, the continuous advancements in technology could potentially result in more intelligent meters that have the ability to identify and regulate energy consumption of specific appliances within a residence or commercial establishment.

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