THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

On possibilities of smart meters switching at low voltage level for emergency grid management

YASIR ARAFAT

Department of Energy and Environment
Division of Electric Power Engineering
Chalmers University of Technology
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Licentiate Thesis at the Chalmers University of Technology

Division of Electric Power Engineering
Department of Energy and Environment
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone: +46 (0)31- 772 1000

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Abstract

Smart Meter (SM) is an advanced remotely readable energy meter with two-way communication capability which measures the electrical energy in real-time or near-real-time and securely sends data to Distribution System Operator (DSO). A smart metering system is an application of SMs on a larger scale, i.e. the application of a general principle on a system rather than on individual appliance. The European Commission (EC) has included ten common minimum functional requirements for electricity smart metering systems. One functionality requirement among these functional requirements is that the SM should allow remote ON/OFF switch to control the supply. Some DSOs who have installed remote ON/OFF switch are currently applying this technique for customers typically one by one when customers are changing addresses, or when contracts are terminated, or have defaulted on their payments. The switching functionalities of the SMs could be used for multiple customers, thereby opening up new possibilities for emergency electrical grid management by excluding prioritized customers. There is an interest to investigate if the multiple SMs switching might have some impacts on the Power Quality (PQ) of the electrical grid and also the challenges in implementing this technique on the existing smart metering system during emergency situation.

In this thesis work, three field tests have been performed on multiple SMs switching focusing on the impact of the SMs switching on the PQ of the grid. A risk analysis was carried out before conducting the field tests. The PQ measurements were done by Power Quality Meters (PQMs) during the multiple SMs switching. Voltage variations and PQ events were recorded in the PQMs. Waveform data of the PQ events were recorded at 12.8 kHz sampling frequency. The test results are then evaluated based on PQ standards. Moreover, performance of the existing smart metering system was investigated during the multiple SMs switching to identify the challenges and possibilities of using multiple SMs switching.

The analysis of the test results show that there were no other PQ events or voltage variations except some transient events which were recorded at some customer level during the reconnection of the SMs. However, the duration of the transient events was only fractions of a millisecond and deviation of the voltage transients were below +/-50% except for few transient events which have deviations of more than +/- 50% but less than +/-60%. This type of transient events may not be able to create damage to sensitive customers' loads. The multiple SMs switching may not have impact on the PQ if the number of customers is low. However, SMs switching for large number of customers might have impact on the PQ which needs to be investigated.

Moreover, the performance of the existing smart metering system during multiple SMs switching shows some limitations on implementing the switching technique for large scale of customers. The identified limitations are e.g., long time requirement for SMs switching and errors in the real-time status update report during SMs switching. Furthermore, the findings show that more research is needed to identify required functions for future smart metering system to implement multiple SMs switching during emergency grid management.

Index Terms: Electrical distribution grid, Power quality, Power quality measurement, Remote switching, Smart grid, Smart meter.

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Yasir Arafat
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List of Abbreviations

AMI	Advanced Metering Infrastructure
AMR	Automatic meter Reading
AMM	Automatic Meter Management
CBA	Cost Benefit Analysis
CS	Central System
CM	Corrective Maintenance
DSM	Demand Side Management
MCU	Meter Data Concentration Unit
DSO	Distribution System Operator
EC	European Commission
EMC	Electro-Magnetic Compatibility
EN	European Standard
EU	European Union
GEAB	Gothenburg Energy AB
GSM	Global System for Mobile communications
GPRS	General Packet Radio Service
HAN	Home Area Network
HEMS	Home Energy Management System
IDS	Intrusion Detection Systems
IEC	International Electro-technical Commission
LV	Low Voltage
PM	Preventive Maintenance
PQ	Power Quality
PQM	Power Quality Meter
PLC	Power Line Communication
P_{lt}	Long Term Flicker severity
P_{st}	Short Term Flicker severity
RMS	Root Mean Square
SCADA	Supervisory Control And Data Acquisition
SG	Smart Grid
SM	Smart Meter
SMsD	Disconnection of Smart Meters
SMsR	Reconnection of Smart Meters
THD	Total Harmonic Distortion
TMDA	Time Division Multiple Access
Ub (%)	Voltage Unbalance

Contents

Chapter 1 Introduction

1.1 Background and motivation

Distribution System Operators (DSOs) worldwide are deploying Smart Meters (SMs) to provide electricity customers improved visibility into their energy consumption. The SMs have been shown to provide benefits to both customers and the DSOs. The SMs can enable demand response to reduce peak load. It can also help to manage voltage for reducing energy consumption. Moreover, the SMs can provide new customer offerings like time-of-use billing and prepayment. Furthermore, smart metering technology is helping the DSOs address modern energy challenges such as optimized grid planning and operation.

The Electricity Directive in the Third Energy Package, Directive 2009/72/EC1, triggered the installation of the SMs in the European Union (EU) countries and it is foreseen that at least 80% of the electricity customers will adopt this technology by 2020. This is subject to a cost-benefit assessment on long-term cost and benefits to the market and the individual customers or which form of intelligent metering is economically reasonable and cost effective [1]. The SMs rollout is progressing in several parts of the world with an early adoption in some parts e.g., in Europe. Over the past years, almost all European countries have performed cost benefit analysis (CBA) of smart metering and the majority of the cases have resulted in a recommendation to go ahead with a rollout [1-8].

Sweden performed a full-scale deployment of the electricity SMs during the years 2003 to 2009 due to mandated monthly invoicing which entered into force on 1st July 2009 and encouraged widespread deployment of Automatic Meter Reading (AMR) technology. Italy and Sweden are the first countries in Europe to complete a near full rollout of SMs [1]. Four EU Member States – Sweden, Italy, Finland, and Malta have completed full rollout of smart meters by 2014 [1].

The European Commission (EC) has included ten common minimum functional requirements for electricity smart metering systems in Recommendation 2012/148/EU [2]. These functionalities include the essential elements that a smart metering system should have to benefit all stakeholders i.e., the customer, the metering and the DSO. The minimum functionalities includes several aspects such as enabling smart metering in a secured and safe environment, commercial aspects of supply/demand and the integration of distributed generation. One functionality requirement among these functional requirements is that the SM should allow remote ON/OFF control of the supply and/or flow or power limitation. This functionality relates to both the demand side and the supply side. It can speed up processes such as when customers are moving home, the old supply can be disconnected and the new supply can be enabled quickly and simply. Moreover, it is needed for handling technical grid emergencies.

Most of the DSOs in Europe have installed remote ON/OFF control in the SM [1,9].The DSOs have the possibility to switch the SM of any customer remotely when needed. Some DSOs in

Sweden e.g., Gothenburg Energy AB (GEAB) who have installed remote ON/OFF control are currently applying this technique for customers typically one by one when customers are changing addresses, or when contracts are terminated, or have defaulted on their payments. The ON/OFF control functionality of the SMs could be used for multiple customers at low voltage (LV) level of the distribution grid, thereby opening up new possibilities to balance electricity consumption and production in emergency situations like natural disaster. The LV distribution grid is the part of the electrical grid from the last substation to the customers. In Sweden, a three phase connection with a voltage of 0.4 kV is usual in this part of the grid where most of the customers are residential, service and industrial sectors. Multiple SMs switching technique could useful to exclude prioritized customers during emergency grid management. How the technology has been functioning in practice has, however, not been fully investigated with regard to multiple SMs switching. There is an interest to investigate if the simultaneous multiple SMs switching might have impacts on Power Quality (PQ) of the grid.

1.2 Objectives of the thesis

The main objective of this research project is to investigate the impact that multiple SMs switching might have on the PQ at LV level of the distribution grid. Specifically, the objective is to perform field tests on the existing smart metering system by switching multiple SMs simultaneously and to monitor the PQ at customer level and also at the 0.4 kV side of the LV substation (10kV/0.4kV). Moreover, the objective is to investigate the possibilities and the challenges of the existing smart metering system of GEAB in implementing the multiple SMs switching for emergency grid management.

1.3 Main Contributions of the thesis

The main contribution of this thesis summarized as follows:

1) Plans of the three field tests to investigate the impact of multiple SMs switching on the PQ at LV level.
2) Risk analysis of the field test on multiple SMs switching.
3) Presentation and analysis of the field test results based on the standards for PQ analysis.
4) Identification of the possibilities and the challenges of implementing multiple SMs switching on the existing smart metering system of GEAB.

1.4 List of Publications

The following list of papers has been published / submitted within the research project:

I. **Y. Arafat,** L. Bertling Tjernberg, S. Mangold, "Feasibility study on low voltage DC systems using smart meter data," in *CIRED 2013, 22nd International Conference and Exhibition on* electricity distribution, Stockholm, 10-13 June 2013.

II. **Y. Arafat,** L. Bertling Tjernberg, P. Anders Gustafsson, "Remote switching of multiple smart meters and steps to check the effect on the grid's power quality," in *T&D Conference and Exposition, 2014 IEEE/PES*, 14-17 April 2014.

III. **Y. Arafat,** L. Bertling Tjernberg, P. Anders Gustafsson, " Experience from Real Tests on Multiple Smart Meter Switching," in *Innovative Smart Grid Technologies Europe (ISGT EUROPE), 2014 5th IEEE/PES*, 12-15 October, 2014.

IV. **Y. Arafat,** L. Bertling Tjernberg, P. Anders Gustafsson, " Possibilities of demand side management with Smart Meters," presented in *CIRED 2015, 23rd International Conference and Exhibition on* electricity distribution, Lyon, 15-18 June 2015.

V. **Y. Arafat,** L. Bertling Tjernberg, P. Anders Gustafsson, " Field test on multiple Smart Meters switching to study the effect on power quality at customers level," presented in PowerTech*, 2015 IEEE/PES, Eindhoven*, 29 June-02 July, 2015.

VI. **Y. Arafat,** L. Bertling Tjernberg, P. Anders Gustafsson, " Experience from Switching Tests of Multiple Smart Meters in Sweden - analysing the effect on Power Quality," Submitted to The IEEE Transactions on Power Delivery in June 2015.

1.5 Thesis Outline

Chapter 2: Introduces the smart metering system and also the standards for measurement and analysis of PQ at LV level.

Chapter 3: Presents three field test plans on multiple SMs switching

Chapter 4: Describes and presents the test results.

Chapter 5: Evaluates the test result on the basis of standards for PQ.

Chapter 6: Concludes the thesis with some ideas for future research work.

Chapter 2 Smart Metering System and Power Quality

This chapter provides an introduction to the concept of smart metering system used in this thesis and gives a review of functionalities and applications of smart metering system. Potential future applications of remote ON/OFF control switch in the SM are discussed. Cyber security issues related to remote ON/OFF control are presented. Finally, standards for PQ measurement and analysis are presented.

2.1 Overview of the Smart Metering System

2.1.1 What is Smart Metering System

Smart metering system is an actual application of the SMs on a larger scale, i.e. the application of a general principle on a system rather than on individual appliance. In the history of metering technology, smart metering system represents the third stage in a chain of developments spanning more than hundred years [10].

In the first stage, the traditional electromechanical meters, which were developed in the late Nineteenth century, have a spinning disc and a mechanical counter display. This type of meters operates by counting the number of revolutions of a metal disc that rotates at a speed proportional to the power drawn through the main fuse box.

The replacement of electromechanical meters with solid-state electronic meters resulted in the second stage in the meter evolution, making it possible to measure energy using highly integrated components. These devices digitize the instantaneous voltage and current by using analog to digital converter. The energy data is displayed on a liquid-crystal display. Once meter data is available in electronic form, it becomes feasible to add communications to the meter, allowing the meter to use AMR to access data remotely via the one-way communication link. This helps eliminate estimated consumptions bills and the need for a meter reader to visit customer.

Smart metering system, the third stage in the meter evolution, broadens the scope of AMR beyond just meter readings with additional features enabled by two-way data communication. A smart metering solution generally delivers a range of applications using an infrastructure comprising networked meters, communication networks and data collection and management systems which is called Advanced Metering Infrastructure (AMI). An AMI can take real-time or near-real-time measurements, provide outage notification and basic PQ monitoring, and support in-home energy applications. It allows data exchange between the SM and the Central System (CS) of DSO, while also allowing customers to have timely and easily accessible information about their usage. The system with AMI can also manage the configuration of all units in the system, which function is referred as Automatic Meter Management (AMM). Moreover, the AMM function can provide basis for meter data management, event and fault management, operation and maintenance.

An overview of a smart metering system can be represented as shown in Figure 1.

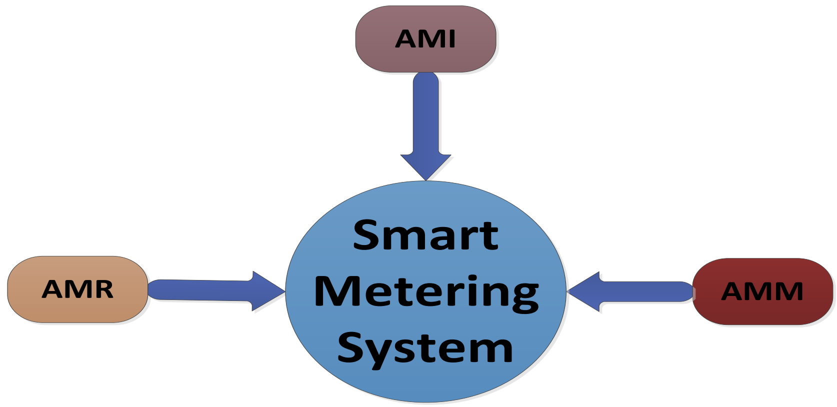


Figure 1: An overview of the Smart Metering system

2.1.2 Parts of a Smart Metering system

A smart metering system generally contains four main parts i.e.; SMs, terminals, Meter data Concentration Units (MCUs) and a CS. The functions of each part are given below:

Smart Meter: The SM is a remotely readable energy meter with two-way communication capability which measures the consumptions of electric energy of a household or industry in real-time or near-real-time and securely sends it to the DSO [11, 12]. This helps eliminate estimated bills for energy consumption and the need for a meter reader to visit individual premises which is required for traditional electricity meter readings. The SM is electrically fed and composed of electronic controllers with digital display and also allows the energy consumption data to be displayed on a device within the home. It has an interface allowing data to be transmitted from the meter terminal to the MCU or directly to the CS. The objectives of the SM are to measure, display and save actual data of electricity consumption. Most SM can also record the energy that the customer feedback into the distribution grid from co-generation sources, such as wind turbines and solar panels. In addition to these, the SM provides opportunity for remote connection and disconnection of the customer power supply. Moreover, alarm functions can be implemented which will send alarm to the CS automatically if someone tries to manipulate the meter. Furthermore, the SM has the capability to receive information remotely, e.g. to update tariff information or switch from credit to prepayment mode.

Terminal: The terminal is the unit which maintains communication between the meter and the MCU. It collects the energy consumption data from the meter and sends it to the MCU or directly to the CS. How often the data is transmitted depends on the requirement. Usually the terminal is integrated in the meter and the DSO can communicate with it. Several techniques are used for remote transmission of the electricity consumption data. The choice of technique depends on the area, number of customers and the available communication infrastructure. The data can be transmitted by using Power Line Communication (PLC), Radio link and/or Global System for Mobile communications (GSM)/General Packet Radio Service (GPRS). The data is collected from the meter in accordance with the internal schedule set by the administrator of the smart metering system.

Meter Data Concentration Unit: The MCU is the unit which supervises and maintains communication with all meter terminals within a specific area. The MCU collects the data from several meter terminals and stores it temporarily. The CS finally collects the data from MCU regularly after a certain interval. The MCUs are usually placed on the LV side of a substation to make a communication path between the SMs and the CS. The MCUs maintain local communication with the SMs and if a meter cannot be reached within a certain time it reports to the CS. The data from each meter is temporarily stored in the MCUs and then the CS collects the data. A MCU can support various MCU management functions such as firmware download, control, setup and information view.

Central System: The CS receives commands from a user through the web user interface and sends the commands to the SMs via MCU and returns result to the user. It acts as a brain where it is decided what to do and at which time. By using the software it can control and configure different units in the system. The CS mostly communicates with the MCU. A communication system is required to be able to transmit data and to control different signals between the SMs and the CS. Functions included in the CS are mainly involves processing of the data and fault management control. The data are the basis for invoice management and statistics which is regularly provided to customers via web based customer portal.

2.1.3 Applications of Smart Metering system

A smart metering system can be used for different applications which can be categorized as follows [14-17]: The applications of the smart metering system can be categorized into two parts based on who is getting benefit from the application e.g., end-users or energy industry.

2.1.3.1 Benefits for end-users

Better bill information: Smart metering system provides actual and more accurate energy consumption data to the customers and timely billing based on actual consumption data. The customer has improved access to their energy consumption data to manage their energy use in an improved way. It has the possibility to request metered data from a metering point at any time.

Energy saving: The customer can have improved control on their energy usage by having real time and continuous picture of their energy consumption and it may help the customer to identify malfunctioning equipment or improving the situation which will lead to energy savings. Energy savings campaigns can be evaluated by using the load profile.

Smart homes: Smart home refers to a home which has automation system to control different home appliances, lighting, ventilation system etc. according to customer’s preferences, outdoor climate and other parameters. Now a day, remote control of appliances, heating and alarm systems become more common. A unified system connecting all appliances would allow more efficient control of energy consumption. The customer can control the individual appliances in response to information obtained from the SM. The meter data can be used to automate energy saving and demand response measure.

Alarm Services: Smart metering system provides a secure communication channel between the customer and the DSOs. This communication system can be used to provide some additional services such as fire alarms, burglar alarms, panic alarms or other safety related alarms.

Prepaid service: The SM may introduce more cost efficient and customer friendly prepaid service compared to traditional prepaid meters due to the advantage of communication system with SM. Only the customer who is in credit will be provided with the power.

Customer usage feedback: The customer will be provided with the information of their usage and thus the customer would be in the position to reduce its energy consumption or to shift its energy use. The customer can get supplementary information or guideline on how to make energy savings by using their usage pattern. The DSOs may offer financial reward to the customers for shifting or reducing energy consumption.

2.1.3.2 Benefits for energy industry

Status of electrical distribution grid: By taking measurements at or near the customer point of connection the loading and the losses of the distribution grid can be known more accurately. It can help to prevent overloading of transformers and lines. A sample can be used to measure the demand in every 1 or 5 minutes and that information can be used for estimation.

Power Quality monitoring: PQ involves the voltage quality of the distribution grid and the current quality of the loads. Most of the voltage quality problems originate from the customers. The SM can provide continuous monitoring of the voltage quality and enables fast and accurate response to ensure the quality. It can also keep the record of power supply interruption and voltage dips to help the DSOs to understand where investments are mostly needed.

Customer Service: Smart metering system can increase the service quality of the customer call center due to availability of real time power consumption data. Remote connection and disconnection of the customer is also possible with the SM. The DSOs can switch any SM remotely according to the necessity of the customers e.g., during changing addresses.

Load analysis and forecasting: Energy consumption data can be used for load analysis. By combining some information with the load profile, the total energy use and peak demand can be estimated and forecasted. This information is useful for retail suppliers and for the DSO to make a plan for operating the power distribution grid.

Demand Response: Demand response means balancing between load and generation in response to electricity prices. For proper operation of the electricity market adequate price elasticity is necessary. Smart metering system can enable demand response by using real time tariff which is an hourly rate applied to usage on an hourly basis.

Integration of renewables: The SM can measure the generation from each unit of renewable source and maintain a balance between the local generation and the demand. The SM can also be used as a communication media to control the local generation.

Analysis of failure: Measurement data from the SM can be used to analyze the cause of component failures and grid outages. It may also help maintenance of the distribution grid components and the customer equipment.

Management of meter: The information of the meter such as database of vendor, type of the meter, configuration settings, working life, record of scheduled or urgent visit of safety and security checks can help the management process of the meter and the customer record. Meter faults and installation errors may be detected with the SM.

Load control: The DSOs can control the load of the customer by using the interface of the SM. The load can be controlled in different ways such as remote connection and disconnection of the total load or remote connection and disconnections of the partial load or remotely limiting the maximum allowed capacity for a metering point.

Illegal customer detection: Some SMs have the capability to detect any illegal attempt to open the meter box or to modify the connections to the meter or reprogram the meter software. The SM can send signals of any illegal attempt to the CS promptly.

2.2 Communication technologies in Smart Metering system

The SM uses two-way communication capability to send and receive information. Several techniques are used for data transmission between the SMs and the CS. Different factors impacts the choice of communication technology such as the number of customers within the area, telecommunication network coverage of the area and the availability of internet connection. However, research is required towards a robust, low power and low cost communication medium that can adapt to multiple environments [18].

Currently used communication technologies for smart metering system can be distinguished as wired communication medium such as PLC and wireless communication medium such as GPRS and ZigBee. Some of the most common communication technologies are given below:

2.2.1 Power line communication:

The dominant technology in wired smart metering communication is PLC which is also known as Power line Carrier. PLC has evolved since 1980 [18]. The PLC technology uses the existing electrical power cable network with a frequency range of 24 kHz to 500 kHz and the data rate is up to 9.6 kbps. It provides a convenient and economical solution which is suitable for densely populated areas. This technology has a main limitation that the low range signal deteriorates with distance and beyond a certain distance such as some few hundred meters, the signal is completely lost. PLC technology is thus used to establish communication between a set of SMs and the nearby MCU. Then the data are encoded by the MCU in digital format and sent to the CS by using the GPRS network. A PLC modem is linked to each SM and to the each MCU which allows the data to be encoded and decoded as an electrical signal of above 50 Hz.

Due to the most cost-effective way for two-way communication, PLC technique has gained higher interest for data communication of SM. Power line is full of various types of noises. The PLC network can be defined as a concentration of homes connected to LV power lines, which are in turn through a transformer connected to the medium voltage network. The MCU can reside on either the LV or the medium voltage lines. The LV distribution side has different kind of loads connected to the network terminal. Several branches of the cable cause impedance mismatches which can produce multipath propagation of the signal in the power lines [19].

Various interferences from the noise and significant attenuation of signal occur in power line. Depending on how the devices are connected and their operating conditions, the impedance and transmission losses and also the noise level of power lines fluctuate greatly. Power line noises can be created from normal operation such as noises by partial discharges on insulators and apparatus. It may also come from switching operation such as isolator switch, circuit breaker and faults. Moreover, noise can be created from the interference of external sources. At the communication channel, the noises from the normal operation are always present and inside a period of power frequency it creates different values of noise level. The noise which comes from switching operations usually has high amplitude of noise and in most of the case it causes short interruption in signal transmission. According to [19], orthogonal frequency division multiplexing modulation technique allows increasing the tolerance to noises generated by the system under different load conditions.

The flow of data over power lines connecting different smart energy devices inside and outside homes impose new challenges. Those devices include SM, power switches, inverters, distributed consumer electronics, sensing and monitoring devices. All of the components need to be reliably connected all the time in any environmental condition and resilient to any interference. The required data throughput for these purposes is low and the data packet size is less than 64 bytes. Based on it, the narrowband PLC is the most preferred choice because it has low power consumption, low cost, higher scalability and flexibility. Moreover, it can be implemented in a full programmable fashion economically [20].

2.2.2 ZigBee Radio

Different radio based communication solutions exist in the world. ZigBee communication system is discussed here since this is what the studied system uses. ZigBee is a suite of high-level communication protocol specifications based on the IEEE 802.15.4-2003 standard [21]. ZigBee uses the frequency band of 2400 MHz to 2483.5 MHz for the globally open standard. The higher frequency of 2.4 GHz means that the data rate should be up to 250 kbps compared to 1 Mbps data rate of Bluetooth. The technology is intended to be simpler and less expensive than other solutions e.g., Bluetooth. ZigBee is used at radio-frequency applications that require a low data rate, long battery life and secure networking. This standard has been developed to meet the growing demand for capable wireless networking between numerous low power devices. Devices in the ZigBee network could include light switches with lamps, in-home displays and consumer electronics equipment. It also offers many potential applications such as Home Area Network (HAN), heating control, home security, industrial and building automation. The high spreading factor of IEEE 802.15.4 at 2.4 GHz and the sixteen available channels can empirically deliver a disturbance free network, even on a citywide network.

The ZigBee network is self-healing, which indicates route rediscovery if messages fail. The signal passes by another node if one node is not working. In the ZigBee network, each meter thus becomes a repeater, and the network becomes stronger. The nodes may act as an independent router. Since the numbers of neighbors are not fixed, it is easy to connect and disconnect new nodes. It occurs automatically in a spontaneous network. Moreover, the ZigBee network can also be easily expanded as new homes are built, or new services need to be added.

ZigBee is suitable for home automation since the reach of the ZigBee signal is stated to be below 250 m with free sight line. However, a reach of more than 2,000 m with free sight line can be attained [22]. Moreover, the average power consumption of ZigBee is very low since the wake up time to be at active mode is 15ms or less. The MCU has a power usage of only 3 W to 4 W, which is not much more than SM consumption. Moreover, the SM does not initiate transmission by itself except for alerts/alarm but answers when data is requested from the CS. Finally, it is advantageous and cost effective for the DSOs since the DSOs own the infrastructure and are independent of other actors.

2.2.3 GPRS

GPRS is a packet-based wireless communication service that provides data rates from 56 Kbps up to 114 Kbps. The GPRS is based on GSM communication. It provides moderate-speed data transfer, by using unused Time Division Multiple Access (TDMA) channels in, for example, the GSM system [23]. In theory, GPRS packet-based services cost users less than circuit-switched services since packets are needed basis rather than dedicated to only one user at a time. The GPRS also complements Bluetooth, a standard for replacing wired connections between devices with wireless radio connections.

The GPRS technique can be used to build a communication network of the smart metering system. The GPRS technique is used in the investigated system of this thesis work for communication between the MCUs and the CS. Investment and operation cost of this technique is high. Service level is fast but there is a possibility of missing values. It has possibilities to add more service but with a high expense.

2.2.4 Comparison between communication technologies

Each communication technology has advantages and also disadvantages. Table 1 presents a comparison between these three communications technologies mentioned above.

Table 1: Comparison between three communications technologies

	PLC	**GPRS**	**Zigbee Radio**
Investment Cost	Low	High	High
Operational Cost	High	High	Low
Service level (data transfer)	Slow/missing values	Fast/missing values	Fast/secure operation
Added service	Hard	Possible but expensive	Easy

2.3 Available data in Central System

The MCUs collect hourly energy consumption data from the SMs and send the collected data to the CS on a regular basis. The SMs send various types of data e.g., hourly energy consumption data, last metering time, meter information, sensor information, total energy consumption of the customer from the beginning. Moreover, the SMs also send the voltages of the time instants when MCUs asked for meter data. It is also possible to make on-demand reading from SMs. With the on-demand readings the CS can get instantaneous voltages and currents of three phases, active and reactive cumulative energy and information of meter along with other information such as last power outage date, relay switch status. Moreover, the SM can send event report automatically to the CS. It can detect different PQ problems according to the configuration e.g., voltage or current variation beyond the threshold level, THD, imbalance current and voltage etc. The SMs can also send the time instants and the duration of the events. Furthermore, the SMs can send alarm in real time to the CS for power outage, tamper detection, low battery etc. The software in the smart metering system can filter the alarms to analyze the severity of the cause of alarm and helps to take necessary steps rapidly and efficiently.

2.4 Common functional requirements for SM recommended by EC

The EC has recommended ten minimum functionalities for smart metering system to serve the EU member states with a solid basis for respective investment of the DSOs, to provide EU regulators with a reference definition and facilitate SM rollout. The functionalities are given below [2]:

For the Customer:

- Provides readings from the meter to the customer and to equipment that he may have installed;
- Updates these readings frequently enough to allow the information to be used to achieve energy savings;

For the Meter Operator:

- Allows remote reading of meter registers by the Meter Operator;
- Provides two-way communication between the meter and external networks for maintenance and control of the meter;
- Allows readings to be taken frequently enough to allow the information to be used for network planning.

For commercial aspects of energy supply:

- Supports advanced tariff systems;
- Allows remote ON/OFF control of the supply and/or flow or power limitation.

For security and privacy:

- Provides Secure Data Communications;
- Fraud prevention and detection.

To allow distributed generation:

- Provides Import / Export & Reactive Metering.

2.5 Remote ON/OFF control

2.5.1 What is Remote ON/OFF control

The SMs can be equipped with an additional remotely accessible switch to allow the DSO to control customer power supply and the switch is referred as remote ON/OFF control switch or remote connect/disconnect switch. Among the ten minimum functionalities recommended by the EC, there was a high consensus on the provision that the SM should allow remote ON/OFF control of the supply [2]. In a power failure scenario, the SM will start functioning automatically after power supply is back since the switch was ON. However, the switch of the SM needs to be reconnected remotely if it is disconnected remotely. Some SMs, however, allow physical reconnection using an optical eye if the remote reconnection command does not function properly. Moreover, the communication signal strength needs to be sufficient to execute SM switching.

2.5.2 Potential future applications of remote ON/OFF control

Several goals can be achieved by using the remote SM switching technique. Some potential applications of remote ON/OFF control with SM are provided below:

A. Demand side management during peak load crisis

A main issue that is discussed now-a-days regarding the electrical grid infrastructure is the problem with congestion during peak electricity demand periods [31]. As the demand has been increasing with time, the power reserve, as it is designed today, may be gradually phased out [32]. Demand Side Management (DSM) can then be necessary to keep balance between the demand and supply. DSM means that the electricity demand is adapted to the electricity production and the available electricity in the grid and it both refers to reducing electricity demand and avoiding load peaks during congestion in the grid. The benefit for a DSO to control the energy use is to be better able to handle congestion situations and decrease the risk of blackouts. The distribution grid generally holds overcapacity to handle peak demand situations. Since, the power reserve that can be started on short notice and agreements might be phased out in future, the implementation of the Smart Grid (SG) and DSM are expected to provide flexibility which will contribute to reducing the need for a power reserve. The key to make DSM more effective and the grid smarter is to fully and dynamically integrate customer's loads, and information about their usage into the operation of the grid. The SMs can help in achieving this target by providing hourly electricity consumption data.

In [33], it is explained that there are two ways of controlling the customer energy use: direct and indirect. Direct control of the energy use means that a contract is made with customers where the customer allows direct control over the power output. The controlling party could be for instance, the DSO or the electricity supplier. Indirect control means giving incentives to the customers based on different types of contracts that will motivate the customers to adapt their electricity use. In this case, no certainty of the customer reaction is given but with experience the supplier and grid owner could predict the reactions. The smart metering system can be used for direct control of demand side in the grid based on contract with the customers. Moreover, using SM switching technique for DSM may help the DSO to exclude emergency service providers and prioritized customers from power outage.

Disconnecting selected customers during peak load crisis can help to avoid overloading of the electricity distribution lines. The DSOs can decide which customers to disconnect and at which frequency level. All disconnection levels need to be remotely configured within the smart metering system software and each customer can be predefined by a different frequency value. This action might allow differentiated and graduated load shedding for more balanced load management and the DSOs may avoid black-outs as has been common practice until today. The reconnection of each customer can also be predefined by the DSO. When the peak load crisis is over, customers will also be gradually reconnected to the grid. The switching functionality of the SMs can help the DSOs to perform gradual and selective load shedding on the customer level without the need to disconnect all customers within a substation area. Pre-selection of load shedding needs to be made in such a way that other prioritized customers such as clinics and pharmacy will not be limited or disconnected, including risk customers such as the elderly.

B. Power to prioritized customers during maintenance work

The DSO might need to perform maintenance work on the grid to clear faults, conduct network reinforcement or upgrade the grid. The maintenance work can either be Preventive Maintenance (PM) or Corrective Maintenance (CM). The PM work is usually planned e.g., to adjust voltage level at LV substation and scheduled before while the CM work is carried out after failure detection to restore an asset to an operation condition. When a DSO performs maintenance work e.g., PM work in an area, most of the time the DSO needs to disconnect power from the substation with the consequence that all customers under that substation lose power supply, including prioritized customers. Sometimes, it can be possible to supply the customers of the impacted area from a nearby substation if the total load falls within the capacity of that substation. But for some area, the total load might exceed the capacity of other substation. In that case, remote switching technique of the SMs can be used to disconnect some customers until the capacity of the other substation is matched. The rest of the customers can then be supplied from a nearby substation while doing maintenance work at the mother substation. In this way, the essential service providers and the prioritized customers can have power supply during the PM or CM work when the DSO needs power shut down from the substation.

C. Outage planning during natural disaster

Natural disasters might damage electric power system components, causing widespread outages over a long period of restoration, resulting in the overloading of distribution lines. To provide power supply to essential service providers during disasters, the remote SM switching technique can be used. This technique can either be used to shed some loads for reduction of line overloading or can be used to continue power supply to the prioritized customers from an active substation or battery storage. This practice may help the DSO handling the critical conditions during natural disasters, and also to ensure continuous power supply to the prioritized customers.

2.5.3 Cyber security issues related with ON/OFF control switch of Smart Meter

Modern SMs commonly have remotely accessible ON/OFF control switch for connection or disconnection of power supply to the household. This unique feature of the SMs is valuable for DSOs but researchers have raised concerns about possible abuse by malicious attackers which could lead to blackouts or affect the stability of the electrical grid, e.g., by disturbing the system frequency.

The remote connect/disconnect capability of the SMs has caught the attention of the security community in recent years [35-37]. Because, the remote ON/OFF control switches of the SMs can either be used as planned or misused by an adversary. Over the last few years, the security community has begun to realize that moving from closed and proprietary networks to open IP networks may be efficient but it can also open up vulnerabilities. The energy companies have not had to face this kind of security problem before. By using the remote switch, the adversary can tamper with the frequency of the electrical grid which could cause a widespread blackout or could potentially harm the electrical grid.

A common misconception exist about security is that if encryption is used, the grid and the devices are safe from attacks. However, the devices may still be vulnerable to an exploit e.g., buffer overflows in devices and sloppy implementations of cryptographic protocols. Also, there is risk that the protocols may not be well implemented in the system. Moreover, an oversight may lead to no change of the default settings [36]. Security measures like data encryption and Intrusion Detection Systems (IDS) offer some level of protection for AMI systems. But, these security measures provide little help if an attacker is able to compromise the system and issue a malicious disconnect commands to millions of SMs [38].

Related work on cyber security issues of SM can be found in some articles. For example, problems related to the communication module with interception and injection of false messages is discussed in [39]. It also presents a scenario showing how the injection of false malicious data lets the adversary gain different benefits from the system. Moreover, a methodology to extract and reverse engineer the firmware from a SM to obtain valuable information such as passwords and communication encryption keys is described in [40]. Furthermore, weakness of the communication channel between the SMs and the CS has been shown in [41]. In [42-44], the model and the functionalities of IDS are covered for AMI system.

So far little work has been done to develop and assess concrete countermeasures that are specific to the known cyber-attacks. Since, this is a relatively new area of research, it is expected that there are other vulnerabilities which are not known yet. A successful attack would have severe economic and political consequences. Significant research efforts can be seen into securing the SG mainly focused on the Supervisory Control And Data Acquisition (SCADA) systems and the transmission grid. But, attacks originating from the distribution side can also have significant effects on the grid. More research is recommended in this new research area.

2.6 Smart Meter rollout

The DSOs worldwide are deploying SMs to provide customers improved visibility into their energy consumption. Moreover, with the use of SMs, the DSOs can enable demand response for a reduction of peak load and also to manage voltage for reducing energy consumption. Furthermore, the DSOs can provide customers some new offerings like time-of-use billing and prepayment. Some examples of SM rollout progress in the several parts of the world are given below:

Smart Meters in Europe:
The EC adopted an energy and climate change package in 2007. The objectives on the initiative states that by 2020, greenhouse gas emissions must be reduced by 20%, there must be a 20% of renewable energy sources in the EU energy mix, and EU primary energy use must be reduced by 20%. Local electricity supply management is expected to play a key role in reaching the ambitious 2020 targets and can be enabled and enhanced by smart metering system which can increase customer awareness and participation. Due to the EU policy recommendations in terms of energy, it is expected that by 2020 most of the European countries will have a majority of energy supply points equipped with the SMs. Smart metering system rollout is progressing fast in Europe [24]. But the pace of smart metering system deployment has been different from one country to the other.

In Europe, four EU member states have already completed full roll-out of the SMs by the end of 2014. Italy and Sweden are the first countries to complete a near full rollout of the SMs [4], while several European countries prepare the take-off. During 2001 to 2008, Italy installed around 36 million SMs. In the years 2003 to 2009, Sweden completed a full roll-out, installing 5.2 million SMs. The smart metering system coverage of Finland was 100 percent by the end of 2013 which indicates 3.3 million SMs installation throughout the country. Malta has also completed a full roll-out of two-hundred sixty thousands SMs by 2014. Most of the countries in Europe have already mandated the SM roll-out with a specified timetable. There are different deadlines in each country from 2017 to 2020. For example, France will install 35 million SMs by 2017, the UK will install 56 million by 2019, and Spain will install 28 million by 2018.

According to [1], sixteen EU member states (Austria, Denmark, Estonia, Finland, France, Greece, Ireland, Italy, Luxemburg, Malta, Netherlands, Poland, Romania, Spain, Sweden and the UK) have decided for large-scale roll-out of SMs by 2020 or earlier. Moreover, seven member states (Belgium, the Czech Republic, Germany, Latvia, Lithuania, Portugal, and Slovakia) got negative or inconclusive outcomes of CBA for large-scale roll-out of SMs. But, Germany, Latvia and Slovakia found the result economically justified for a specific group of customers. The remaining four member states (Bulgaria, Cyprus, Hungary and Slovenia) have not made the outcome of their CBA available yet.

The Swedish Parliament approved monthly reading of all electricity meters from 1 July 2009, supported by the findings of the Swedish Energy Agency that more frequent meter reading would generate economic net benefit. Since July 2009 monthly meter reading is required for smaller customers with a fuse of less than 63 A and hourly metering should be performed for larger customers [13]. From 1st October 2012 a new regulation was introduced, that allowed the customers to require hourly metering of their electricity consumption, if they had an hourly energy contract with their retailer [25].

Smart Meters in America:
According to [26-27], North America has the world's highest penetration of the SMs, exceeding 50 percent. A number of states, including California, Texas, Florida and Pennsylvania have approved DSOs plans for massive SM deployments, while others such as Virginia have turned down major project proposals. As of April 30, 2014 16.18 million SMs have been installed in US, which has covered around 12% of US customers [28]. In Canada, the provinces of Ontario and British Columbia have introduced mandatory requirements for smart electricity meters for all customers. In Latin America, Brazil is leading the region in SM rollout with around 3% customers of the country covered by 2014.

Smart Meters in Asia:
In Asia, East Asia is in the earliest phase of the roll-out of SM. Large-scale rollouts of SM to residential customers recently begun in Japan and South Korea. Japan already has the world's most advanced grid monitoring systems [27] and several of the leading DSOs have announced plans for SM deployments over the next ten years. South Korea has adopted a national plan for the construction of a SG by 2020. China has begun deploying a new generation of more advanced electricity meters, which are prepared for two-way communication. China is on track to reach near hundred percent penetrations of SM by 2015 [27].

Smart Meters in Middle East:
The deployment of the SMs in the Middle East is still in its early stages. Jordan, Lebanon, Syria, Iraq, Yemen, and even Oman and Bahrain in the Gulf, have yet to start the introduction of the SMs. Utilities in Saudi Arabia, Qatar and Dubai, are still in the pilot phase. The rest of the countries are actively deploying the technology. But only one DSO in the UAE, Abu Dhabi's ADWEA, has fully completed the phase-one rollout of the SMs for electricity and water [29].

2.7 Power Quality

2.7.1 What is Power Quality?

PQ is often defined as the electrical grid's ability to supply a clean and stable power flow and determines the fitness of electric power to consumer devices. The aim of the electric power system is to generate electrical energy and deliver this energy to the customer equipment at an acceptable voltage. With an ideal power system, each customer should perceive the electricity supply as an ideal voltage source with zero impedance. In this case, the voltage should be constant whatever the current is. But, the reality is not ideal. The electric power system connects many customers. Different customers have different patterns of current variation, fluctuation and distortion, thus polluting the voltage for other customers in different ways. Moreover, different customers have different demands on voltage magnitude, frequency, waveform, etc.

PQ is the combination of voltage quality and current quality [58]. Voltage quality concerns the deviation between reality and ideal. The ideal voltage is a single frequency sine wave of constant amplitude and frequency. Similarly, current quality concerns the deviation of the current from the ideal where an ideal current is a single-frequency sine wave of constant amplitude and frequency, with the additional requirement that the current sine wave is in phase with the voltage sine wave.

PQ disturbances e.g., deviations of voltage and/or current from the ideal can be classified as two types variations and events. The classification is based on the measurement procedure of the characteristic of voltage or current.

The term 'Variations' refers to the small deviations of voltage or current characteristics from its nominal or ideal value. For example, the variation of root mean square (rms) value of voltage from their nominal values, or the harmonic distortion of voltage and current. Variations are disturbances in the electric power system that can be measured at any moment in time.

The term 'Events' refers to the larger deviations of voltage or current characteristics from its nominal value that only occur occasionally, e.g. voltage interruptions or transients. The events are disturbances in the electric power system that start and end with a threshold crossing. The events require waiting for a voltage or current characteristic to exceed a predefined threshold level.

A greater part of all electrical equipment used today, is built up of electronics that not only create disturbances on the electrical grid but also more sensitive to poor PQ than most of the traditional electrical appliances. The introduction of increasing amount of electronics appliances means that the electrical grid is affected by new types of disturbances from connected loads, e.g., harmonic related problems, transients and flicker. Moreover, single phase loads and loads with higher starting currents are becoming more common in contributing disturbances like unbalance and voltage dips. Poor PQ increases loss in electrical grid, which in turn leads to higher costs for the transmission and distribution system operators. Furthermore, the collaborative effects of these different types of loads can manifest themselves in different ways, e.g., cables and transformers overheating and light bulbs having shorter lives.

2.7.2 Standards for Power Quality at low voltage level

The standard defines what is meant by good PQ and what demands the customers can put on the DSOs. A number of different norms and regulations have been introduced to give guidance for defining good PQ. The international standards on PQ can be found in the International Electro-technical Commission (IEC) documents on Electro-Magnetic Compatibility (EMC). There is a common European standard for voltage quality, EN 50160 [44]. According to an investigation by Council of European Energy Regulators, many European countries have adopted or acknowledged all or some parts of the standard. Several countries have written their own PQ documents, especially on harmonic distortion e.g., Sweden has adopted their own PQ standard, EIFS 2013:1 (Swedish regulation) [46]. The new standard EIFS 2013:1, established by the Swedish Energy Markets Inspectorate is somewhat similar to EN50160 and an important step towards SG. Moreover, the IEEE has published a significant number of standard documents on PQ e.g., IEEE 1159 [45] for monitoring electric PQ.

2.7.3 Power Quality monitoring

Monitoring of voltages and currents provides the network operator information about the performance of their network, both for the system as a whole and also for individual locations and customers [57]. Moreover, monitoring and measuring plays a key role in the concept of SG. Measuring PQ at the end customer is important but even more important is to measure in the grid to discover potential issues at an early stage. The change in the types of loads connected to the power system puts additional pressure on grid operators to monitor and record various aspects of network performance. There are some guidelines for PQ monitoring e.g., CIGRE/CIRED JWG C4.112 [57]. The guideline provides information about measurement locations, processing and presentation of measured data. Moreover, types of monitoring e.g., continuous or short-term, monitoring location, monitored parameters, sampling rate, averaging window are mentioned in the guideline. There is also a measurement standard (IEC 61000-4-30) which divides the measurement instruments into different classes (A/B), where class A means that the measurement instrument can be used as a reference instrument [47]. This thesis work used class A Power Quality Meters (PQMs) to measure the PQ in accordance with the applicable norms.

Chapter 3 Field test on multiple Smart Meters switching

This chapter provides an overview of the field tests on multiple SMs switching. The chapter begins with an introduction to the investigated smart metering system, and test locations selection and PQ measurement methods. Finally, the test procedure, a review of the risk analysis, and the test scenarios are presented.

3.1 Investigated Smart Metering system and the Test locations

3.1.1 Communication technology and functionalities

GEAB, a DSO in Western Sweden, has installed approximately 265,000 SMs with remote ON/OFF control switch in Gothenburg city of 500,000 citizens and the SMs are in operation since 2009 [22]. GEAB is one of the few companies in Sweden which has installed remote ON/OFF control switches in the SMs. A city-wide wireless mesh network with AMM system is created. The meter reading unit is integrated with a ZigBee system on chips and networking software is used to create a wireless meshed network so that the SMs can communicate with each other and route data reliably. The SMs communicate through ZigBee with approximately 8,000 MCUs or concentrators. The ZigBee network is built up as a self-configuring mesh. Only 20 repeaters had been installed because of the advantage of the mesh network [22]. GPRS or optical fiber is used to connect the MCUs to the CS. Figure 2 shows the communication technologies used in the investigated smart metering system. The SMs send data to the CS and also receive command from the CS via the MCUs.

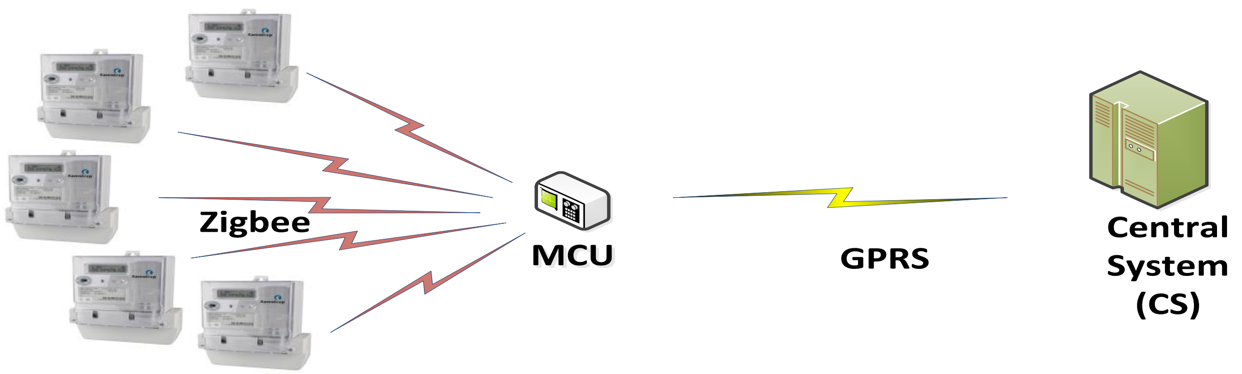


Figure 2: Both way communication technologies used in the investigated smart metering system

The investigated smart metering system provides several functionalities which are already in use e.g., hourly readings, on-demand readings in real time, remote connect/disconnect, power-failure alarm in real time, monitoring of power usage and voltage levels, and also other advanced functionalities. Remote connect/disconnect were the first so-called AMM functionalities put to use. Hourly metering values are collected daily from the SMs. On-demand readings are mainly used in the customer contact center for discussions with customers. Moreover, real-time alarms for power failures are reported to the CS continuously. The smart metering system helps GEAB with many other benefits, such as improved customer service and dialogue, improved monitoring of the low-voltage grid, improved quality of data for grid planning as well as opportunities for new customer services.

3.1.2 Area selection for multiple SMs switching tests

This thesis work includes several field tests on remote multiple SMs switching to investigate the impact of multiple SMs switching on the PQ at LV level [48-50]. The ability of the investigated smart metering system for doing multiple SMs switching and also the performance of the system during switching are studied practically from field tests. The main goal of the field tests is to investigate the impact of multiple SMs switching at the end customers level and also at the LV substation level. This thesis work selected three areas for the tests within Gothenburg city. The tests were performed during the planned outage work of the DSO to avoid extra power outage of the customers only for the tests. Three areas were selected among the areas where GEAB had planned to conduct PM work by interrupting power supply to the customers. Table 2 shows a summary of the three test areas:

Table 2: Summary of the three test areas

	Area Type	Substation type	Transformer ratings	No. of customers	Customers switched with SM	No. of MCUs for the area
Test 1	Residential	10/0.4 kV	500 kVA	12	12	1
Test 2	Residential	10/0.4 kV	800 kVA	37	37	4
Test 3	Residential	10/0.4 kV	800 kVA	177	86	3

3.2 Power quality measurements during SMs switching

The SMs are configurable to measure a limited set of voltage quality disturbances e.g., the supply voltage variations. However, PQMs were used in parallel with the SMs to measure different PQ parameters. The test results presented in this thesis work are from portable PQMs which were used for temporary and short-term PQ monitoring at the customer site and also at the substation. The PQMs stayed at the test location during the test period and captured a sample of measurements. The PQ measurements carried out in accordance with Class A of IEC 61000-4-30 [47]. Flagging was used according to the standard to prevent double counting. The phase to neutral voltage was measured to evaluate the voltage quality.

The following disturbances were covered in the analysis:

- ✓ Supply voltage variations;
- ✓ Flicker;
- ✓ Voltage unbalance (%);
- ✓ Total Harmonic Distortion (%);
- ✓ Voltage sag;
- ✓ Voltage swell;
- ✓ Transient

The PQMs measured and recorded the PQ data during the field tests. The data were recorded during the SMs switching period and also during normal operation period. The PQ data during the switching period are compared with the PQ data during normal operation in Chapter 5.

3.2.1 Selection of PQ monitoring locations

In LV grids, it is recommended to perform PQ measurements at the point of connection of a selection of customers [51]. In this thesis work, during all the three tests, four LV customer locations were selected among all customers in the area. In the first two tests, four customers were selected for PQMs installation based on their energy consumption history. The customers with higher energy consumptions were chosen to get best measurement results from the PQMs. But, in the Test 3, an additional criterion was added in the selection of measurement locations. The distance between the end customers and the LV substation was also considered during monitoring locations selection in order to see the variations of impact at different locations. Two measurement locations were selected from the test area, which were close to the substation while the other two selected locations were far from the substation. The LV substations of the selected areas were also a PQ monitoring location during each test. The PQ was monitored to investigate the impact of multiple SMs switching both at the end customers level as well as at the substation level. Hence, four PQMs monitored the PQ at a selection of connection points of four customers throughout the selected area. Moreover, one PQM monitored the PQ at the substation in the same area. Table 3 shows the number of PQMs installed during each test and also the locations of the PQMs. Moreover, the Table shows if the SMs of the customers with PQMs were switched or not during the tests. As seen here, the SMs associated with the four PQMs were switched during the first two tests while two SMs among the four SMs associated with the PQMs were excluded from remote switching during the Test 3.

Table 3: Number of PQMs installed during each test and also the locations of the PQMs

	No. of PQMs used in the Test	PQM at the LV substation	PQMs at LV customers level	Customers having PQMs switched	Customers having PQMs not switched
Test 1	5	1	4	4	0
Test 2	5	1	4	4	0
Test 3	5	1	4	2	2

3.2.2 Parameters recorded during the test

Different parameters were measured and recorded in the PQMs e.g., average voltages, currents, powers, and flickers. The maximum and minimum values of different parameters were also monitored in addition to parameter averages over a certain period. A short time window was used to monitor the PQ during the test. In the first two tests, all parameters were recorded with one-second data interval except for the short term flicker and the voltage unbalance U_b (%) values which were recorded with ten-minute and one-minute time window respectively (according to the default settings of the PQMs for these parameters). However, for the Test 3, one-second time window was used for all parameters. Table 4 shows the time window used in PQMs for different parameters during the three tests.

Table 4: Time window used for different parameters measurement

Parameters	Time Window for the Test 1	Time Window for the Test 2	Time Window for the Test 3
Average Phase to neutral voltages	1 sec	1 sec	1 sec
Average phase currents	1 sec	1 sec	1 sec
Average powers	1 sec	1 sec	1 sec
Average values of power factor	1 sec	1 sec	1 sec
Short term flicker	10 min	10 min	1 sec
Voltage Unbalance U_b (%)	1 min	1 min	1 sec
Total Harmonic Distortions (THD) (%)	1 sec	1 sec	1 sec

3.2.3 Event triggering

The PQMs used in this thesis work, allow the users to select a triggering method. The triggering method was used to record waveform data when the PQM triggers an event such as voltage sag or swell, rapid voltage change and transients. The triggering limits were used in accordance with Class A of IEC 61000-4-30. There is no standardized method for the detection of transients, neither transient overvoltage nor transient overcurrent [51]. A limit of +/- 50% of the nominal value is used as a normal practice for triggering transient events in Sweden and this limit was used during the Test 1. But, during the Test 2 and the Test 3 a lower limit was used for triggering transient events which was +/- 25% of nominal value. The reason was to investigate on small transient effects during multiple SMs switching. The limit used for triggering voltage sag/swell event was +/- 10% of the nominal voltage. Table 5 shows the limits used during the tests.

Table 5: Threshold limits used to record the PQ events during the tests

	Voltage Sag/swell	Slow voltage variation	Rapid voltage change	Transients
Test 1	+/- 10%	+/- 10%	3% for ΔUstat and 5% for ΔUmax	+/- 50%
Test 2	+/- 10%	+/- 10%	3% for ΔUstat and 5% for ΔUmax	+/- 25%
Test 3	+/- 10%	+/- 10%	3% for ΔUstat and 5% for ΔUmax	+/- 25%

3.2.4 Data sampling:

The PQMs recorded average values of different parameters such as phase voltages and currents with one-second data interval for the whole test period. Waveform data was recorded for the triggered PQ events e.g., transient events at 12.8 kHz sampling frequency. The PQMs recorded waveform data for a number of cycles before and after the events were triggered e.g., waveform data of ten cycles for a transient event; two cycle before and eight cycle after the event triggered.

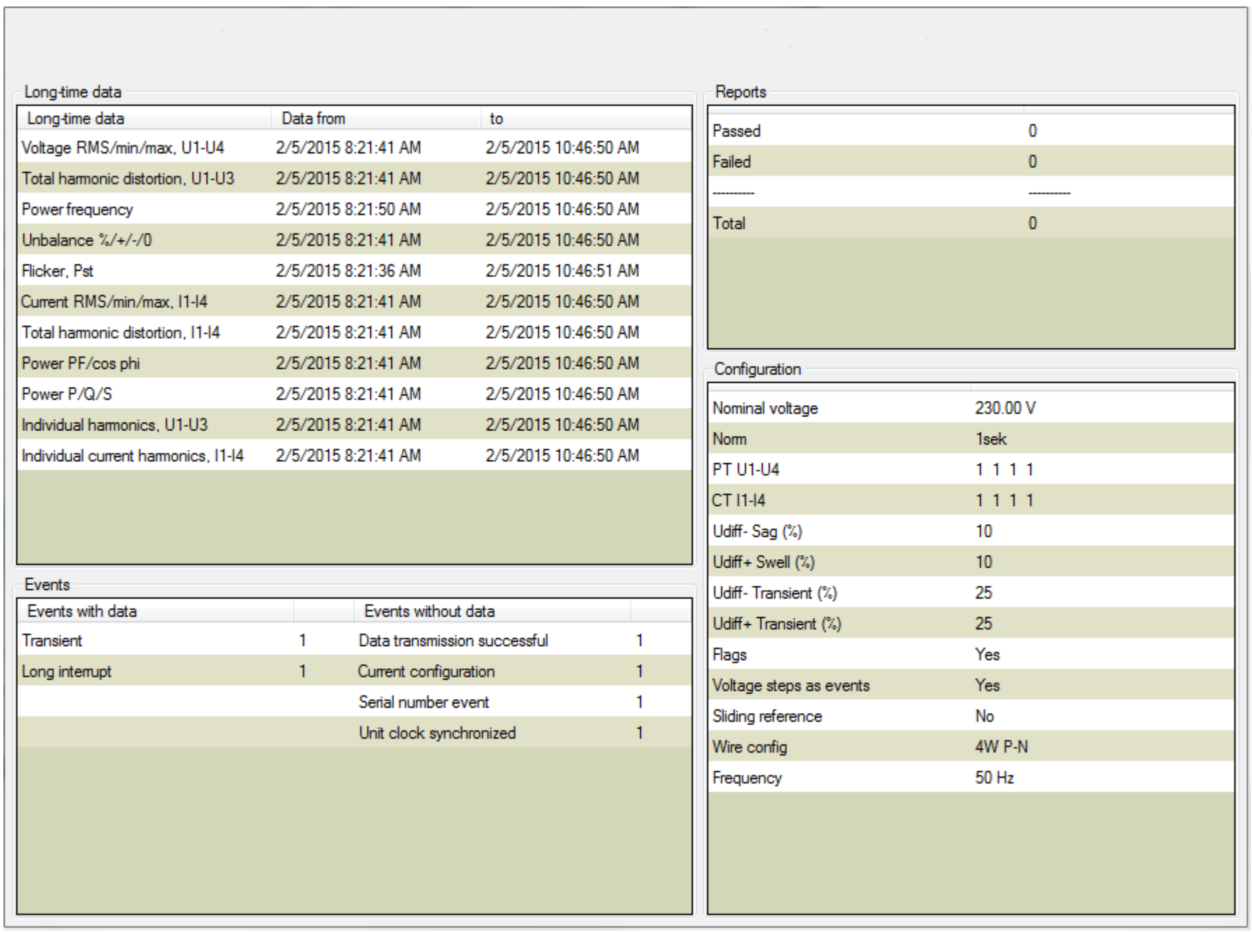
3.2.5 Reference voltage

The reference voltage used to relate the size of voltage-quality disturbances to, is in accordance with EN 50160 [44]. The reference voltage was equal to the nominal voltage, in this case 230 V phase-to-neutral voltages.

3.3 Measurement method of Power Quality Meters

3.3.1 Summary report of the Power Quality measurement

The PQMs measured values of different parameters based on the configuration of the PQMs. The waveform data recorded only for the triggered events due to the limitation of the memory of the PQMs. After the test, the data were transferred to a computer for further analysis. A software tool which was provided by the vendor of the PQM, was used for preliminary data analysis e.g., analyzing waveform data of the PQ events. Five data files were received from each test. Each data file shows a summary report as shown in Figure 3.



Long-time data

Long-time data	Data from	to
Voltage RMS/min/max, U1-U4	2/5/2015 8:21:41 AM	2/5/2015 10:46:50 AM
Total harmonic distortion, U1-U3	2/5/2015 8:21:41 AM	2/5/2015 10:46:50 AM
Power frequency	2/5/2015 8:21:50 AM	2/5/2015 10:46:50 AM
Unbalance %/+/-/0	2/5/2015 8:21:41 AM	2/5/2015 10:46:50 AM
Flicker, Pst	2/5/2015 8:21:36 AM	2/5/2015 10:46:51 AM
Current RMS/min/max, I1-I4	2/5/2015 8:21:41 AM	2/5/2015 10:46:50 AM
Total harmonic distortion, I1-I4	2/5/2015 8:21:41 AM	2/5/2015 10:46:50 AM
Power PF/cos phi	2/5/2015 8:21:41 AM	2/5/2015 10:46:50 AM
Power P/Q/S	2/5/2015 8:21:41 AM	2/5/2015 10:46:50 AM
Individual harmonics, U1-U3	2/5/2015 8:21:41 AM	2/5/2015 10:46:50 AM
Individual current harmonics, I1-I4	2/5/2015 8:21:41 AM	2/5/2015 10:46:50 AM

Events

Events with data		Events without data	
Transient	1	Data transmission successful	1
Long interrupt	1	Current configuration	1
		Serial number event	1
		Unit clock synchronized	1

Reports

Passed	0
Failed	0
---------	---------
Total	0

Configuration

Nominal voltage	230.00 V
Norm	1sek
PT U1-U4	1 1 1 1
CT I1-I4	1 1 1 1
Udiff- Sag (%)	10
Udiff+ Swell (%)	10
Udiff- Transient (%)	25
Udiff+ Transient (%)	25
Flags	Yes
Voltage steps as events	Yes
Sliding reference	No
Wire config	4W P-N
Frequency	50 Hz

Figure 3: A summary report from a PQM used during the field test [60]

The summary report shows the starting time of data record, and the end time of data record for different parameters. The end time of data record refers to the time when the data was transferred from the PQM to the computer and for this reason the end time is different for different PQMs. In reality, the data of different parameters were recorded until the PQMs were at the test location. From the moment of PQM disconnection, the data is shown as ‘NAN’ until the PQM is hooked up to the computer system. The summary report also shows the number of events recorded during the measurement period e.g., transient event. The disconnection and reconnection of the breaker of the substation, which was intentional for planned PM work, was recorded as Long interrupt event in each PQM. Moreover, each summary report shows the configuration of the associated PQM e.g., the triggering limits of different measurement parameters which were recorded for the test period with data interval of one-second.

3.3.2 Power Quality event

The PQ measurement system used in this thesis work shows the details of the recorded PQ events. It also shows the wave shapes of the voltages and the currents for the associated events. The wave shapes of the voltages and the currents were recorded for a short period e.g., 20 ms; when an event was triggered. Figure 4 shows the voltage and current wave shapes for a transient event recorded at a customer level during a field test. As seen here, the event report also indicates the time instants of the events and the duration of the events. Moreover, the report shows - on which phase the event was recorded and the peak value of the transient voltage for the events. The PQ events are discussed more in Chapter 5.

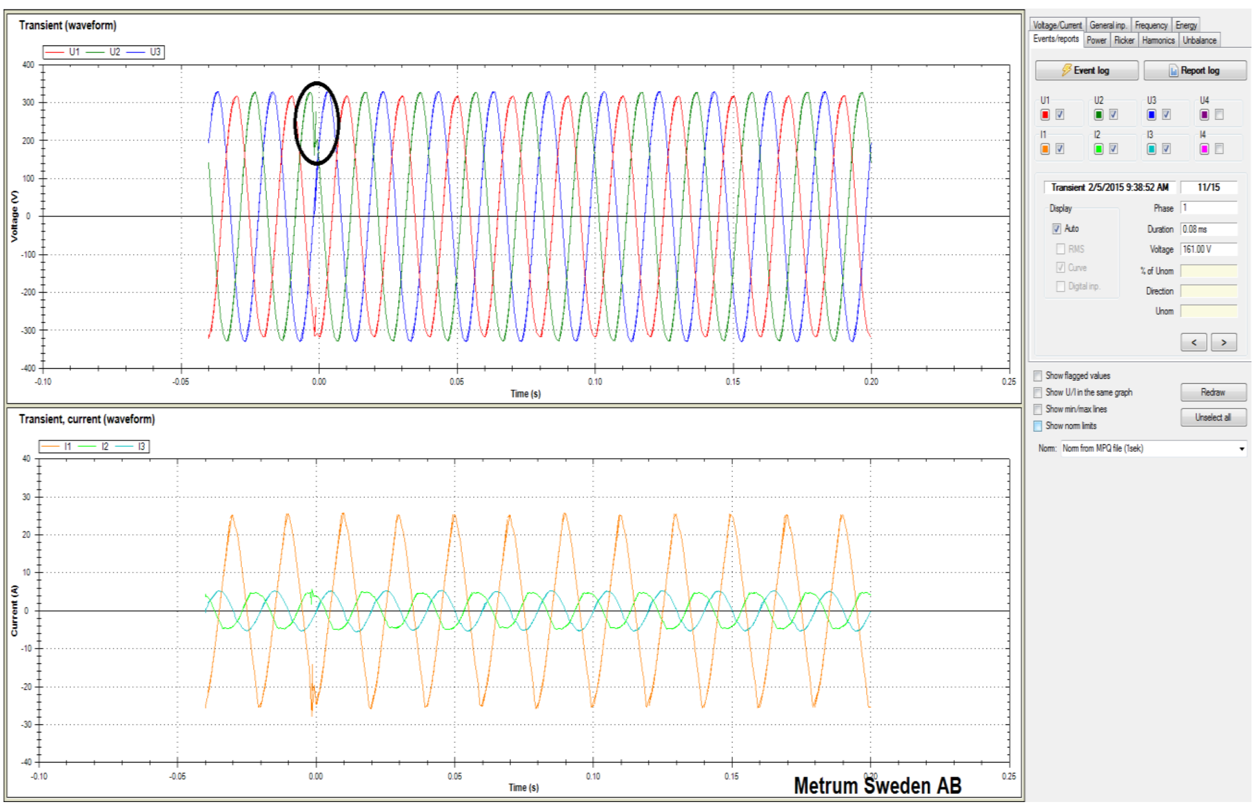


Figure 4: PQ Event recorded in a PQM used during a field test [60]

3.4 Test approach

The DSOs conduct regular PM work on the distribution grid which is planned. For PM activities, the DSOs make a planned outage plan for different areas. All customers that will be impacted by the PM work get information about expected down time, at least one week before the PM work. In this thesis work, three areas were selected to carry out field tests on multiple SMs switching.

The DSOs generally start PM work by first disconnecting the power supply of the selected area from the LV substation. The power supply to the customers is normally switch back immediately after completion of the intended task. In this thesis work, a new additional approach was taken for disconnecting and reconnecting the customers. The customers in the selected area were first remotely disconnected by switching their SMs and after that the power supply of the whole area was disconnected from the substation. In the first two tests, all SMs in the test area were remotely disconnected but in the Test 3 almost half of the SMs were remotely disconnected while other half of the customers had power supply until disconnection made from the substation. The breaker of the substation was reconnected again after completing the PM work. Finally, the selected SMs were reconnected remotely. The time plan of multiple SMs switching tests is shown in Figure 5.

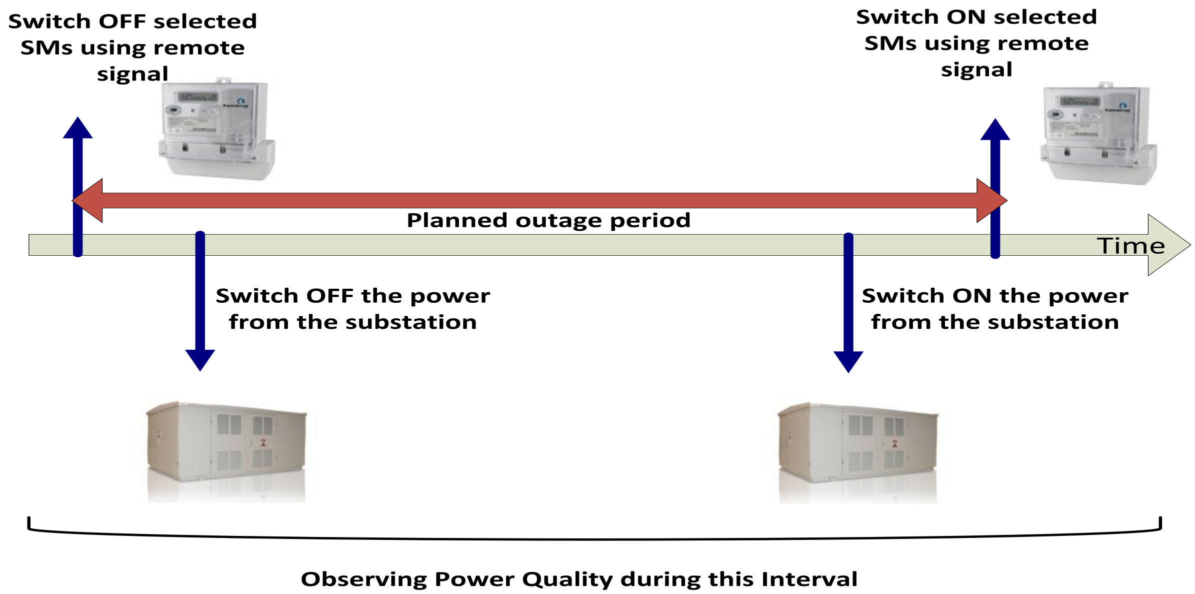


Figure 5: Time plan of multiple SMs switching tests

An individual test plan was made for each test before conducting the field test. The test plans were made after having group discussions within GEAB with people having expertized on the power system, measurement system and the smart metering system. PQMs were installed at the selected monitoring locations at least one day before the tests. However, the data of the PQ measurements were recorded from few minutes before the beginning of the test period and it was done due to data storage capability limitation of the PQMs. Moreover, several people from GEAB were at the test locations during the tests with necessary preparations to handle any emergency situations like SM replacement if needed. The tests were performed by following few common steps as shown in Figure 6.

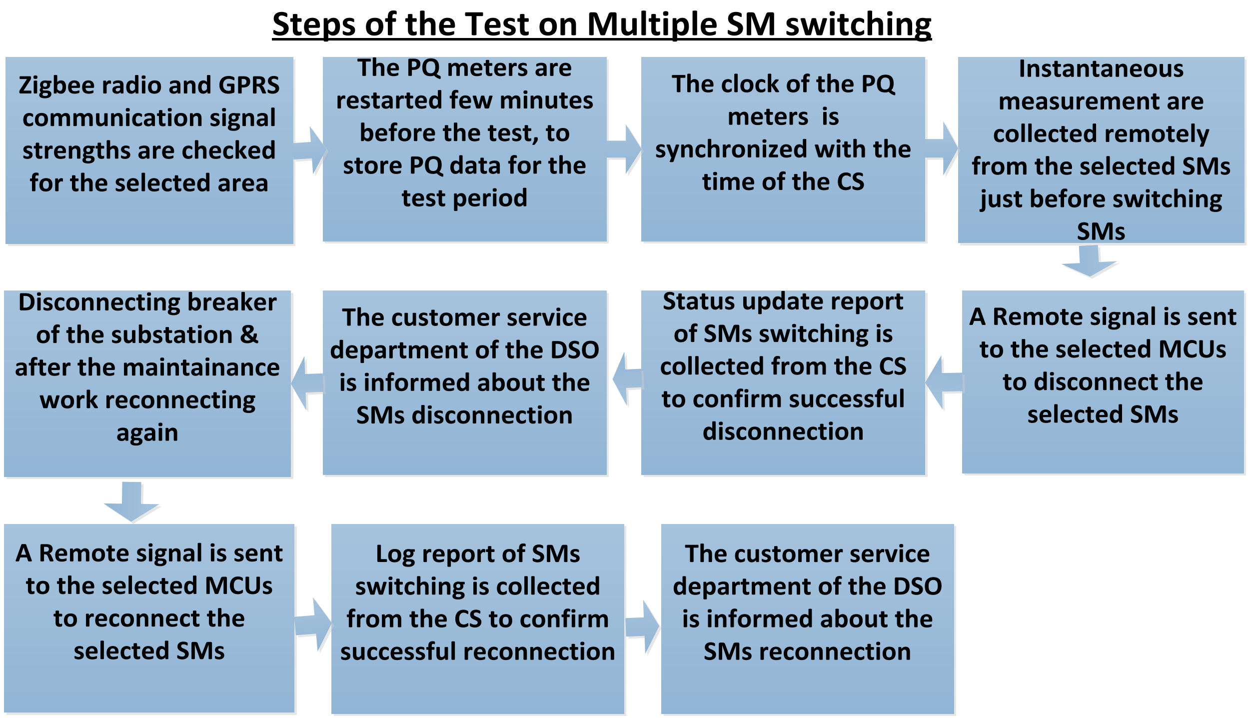


Figure 6: Block diagram of the test steps on multiple SMs switching

First of all, the communication signal strengths of the selected area were checked for both the ZigBee network and also the GPRS network. The PQMs were made ready with full memory capability to store the data of all assigned parameters with a certain data interval for the test periods. The clocks of the PQMs were synchronized with the clock in the CS of GEAB to compare the time instants of measurements later in the analysis.

Real-time measurements of voltages and currents were taken from the SMs remotely few minutes before sending a command to switch the SMs. After that, a command was sent to all the selected SMs via MCUs to disconnect the SMs. The disconnect command was sent from the CS when the planned outage period started. The customer service department of GEAB was immediately informed about the successful disconnections of the SMs.

Adjusting voltage level at the substation was the main purpose of planned outage during each test. For this reason, the power supply of the area was disconnected from the substation to use the tap-changer. The power supply of the area was reconnected again from the substation after adjusting the voltage level. At this stage, real-time measurements were taken again from the SMs to make sure that all the SMs are back into function state and contribute to the system availability. Finally, a new reconnect command signal was sent from CS to reconnect all the selected SMs. The customer service department of GEAB was again informed about the successful reconnections of the SMs. The status update reports of SMs disconnection and reconnection and also the data from the PQMs were collected for PQ analysis. The overall process of the SMs switching were completed within the planned outage period for the first two tests. However, switching during the Test 3 took longer than the planned time due to communication problems.

3.5 Risk analysis of multiple SMs switching test

This thesis work performed risk analysis of the test before conducting the field tests on the customers [31]. Figure 7 shows the various aspects considered for the risk analysis. Different time factors were taken into account for the risk analysis e.g., time requires to switch a SM remotely, battery backup time of the SM and the MCU, communication delay and the time required to replace a SM if something happens during the test. Moreover, expected effects on PQ were discussed within the project group to select which parameters need to be recorded in the PQMs. Furthermore, the ability of the existing MCUs for multiple SMs switching was checked. It is found that the investigated MCUs can execute multiple SMs switching but switches one SM at a time. This thesis work also investigated the possible effects of planned outage work on the test result e.g., effect of substation switching on the test result. Since, the DSO planned to adjust only the voltage level during the PM, thus the effect of the PM work on the test result was not expected. Moreover, the locations of each SM were checked to ensure easy physical accessibility to every SM if something happens. Because, any SM might need replacement with a new SM if there is no ZigBee communication. Possible risks associated to weak signal strength of the ZigBee and GPRS communication network were also investigated. Finally, various customer related issues were considered during the risk analysis e.g., conveying message clearly to the customers about the test on PQ while installing the PQMs at their premises. Measures were also taken to avoid customer’s confusion about the power interruption by updating the customer service department of the DSO time to time during the tests.

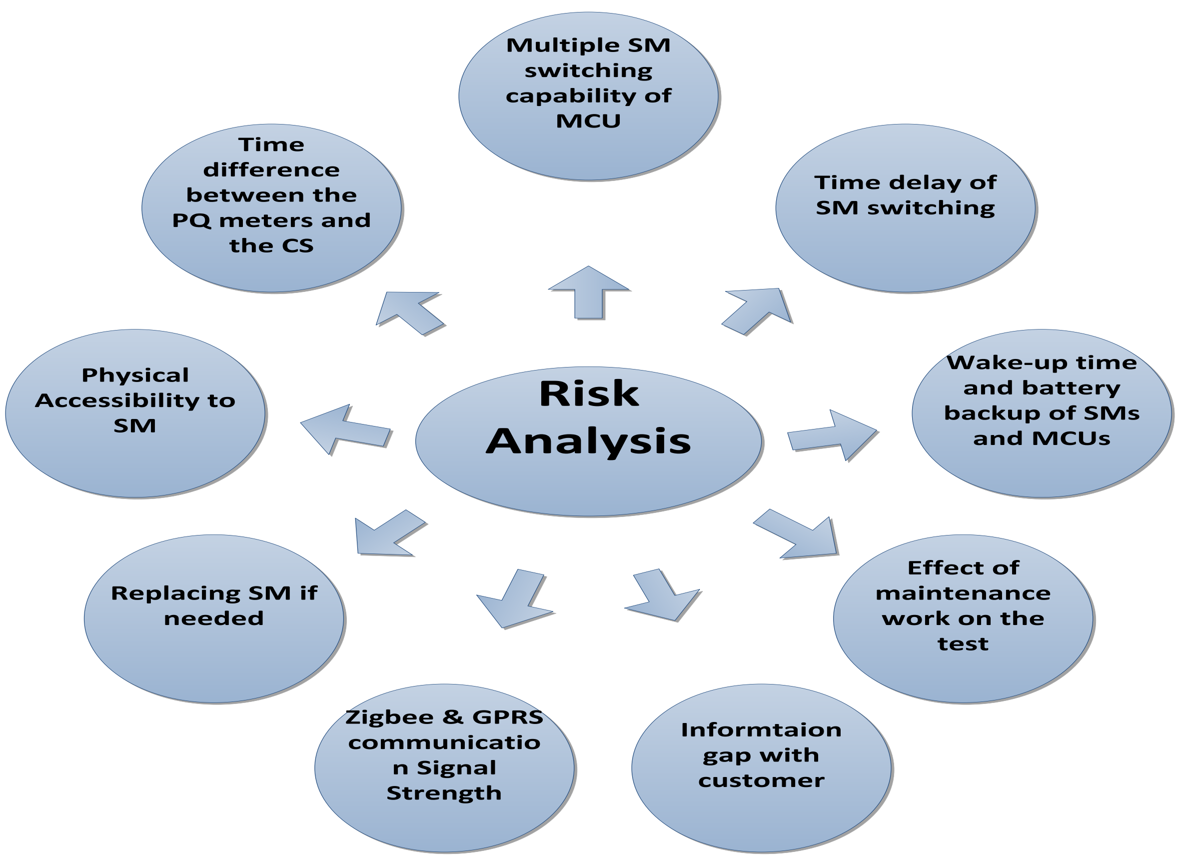


Figure 7: Risk Analysis of the test on multiple SMs switching

In this thesis work, possible risks of doing the field tests on real customers were analyzed. Moreover, possible consequences associated to those risks were investigated to take necessary precautions for minimizing the consequences. Figure 8 shows the level of risks and also the severity of the possible consequences. Different colors are used to indicate low, medium and high probability of the risks and also different colors are used to indicate the low, medium and high level of consequences.

Possible Risks	Possible Consequences	Precaution
Zigbee signal strength may be weak during the test.	SM will not be reachable from CS during the test.	Zigbee signal strength needs to be checked before sending the remote signal to the SM.
GPRS signal strength may be weak during the test.	SM will not be reachable from CS during the test.	GPRS signal strength needs to be checked before sending the remote signal to the SM.
Problem in executing command by MCU.	SM will not be reachable from CS without changing the mother MCU ID for those SMs.	Other MCU can be used to send command to the SM. Need to have a decision about which MCU needs to be used.
MCU may lose power and battery backup may not be sufficient enough.	Consequence will not be serious because MCU will store its data in the memory before it dies.	No precaution is required as the MCU starts very quickly and data will be available fast. It will not hamper the test result.
SM may not respond to the remote signal of switching OFF the breaker.	The SM needs to be disconnected manually or will be disconnected when the substation power is switched OFF.	No precaution is required as the SM will not be required to switch ON using remote signal.
SM may not respond to remote signal of switching ON the breaker.	The SM needs to be replaced with a new SM which is already switched ON and the customer will not get power until the meter replaced with a new one.	New SM and persons from service department should be available during the test to replace the SM as soon as possible.
Duration of load shedding may be longer than scheduled due to any problem.	Customers may make phone calls to the customer service center and service people may misunderstand the situation if they are not well informed about the test.	Customer center and operation department needs to be well informed and updated about the test.
Customers may get annoyed if power is unavailable for longer than expected.	The customer may file a complaint to GEAB and may claim for compensation.	Steps need to be taken to ensure that customers are well informed about the situation and to ensure the power back as soon as possible.
Newly replaced SM may take long time (around two hours) to be available in the CS.	It will not be possible to send remote signal to the newly replaced SM until it is available in the CS. Information will come to the system when it is available and will have no effect on the test.	No precaution is required as the newly replaced SM is already switched ON from the beginning and the data will be stored in SM.
Customer may not be at home when it is necessary for GEAB to replace the SM due to any fault.	This will make delay to replace a non-functioning SM by the service person and the customer will be out of power during that period which is unexpected for the customer.	The SMs those are not accessible to the service person in absence of customer need to be excluded from remote switching.

Low Medium High Low Medium High

Figure 8: Possible risks, associated consequences and precautions for the tests

3.6 Test Scenarios

An overview of the three test scenarios and the time periods of the SMs disconnections (SMsD) and also the time period of the SMs reconnections (SMsR) are presented in this section. This thesis work started field test with a small number of customers and the number of customers affected by the tests have increased from Test 1 to Test 3.

3.6.1 Test 1 Scenario

Test 1 was carried out during summer period when the load typically is low and the temperature is high. In the test area, twelve residential customers were connected to a 500 kVA transformer. The fuse ratings of the customers were between 16A to 35A except for one customer who had a fuse of 50A rating. All customers in the area had three phase connections which is general standard in Sweden. Four PQMs were connected temporarily at four selected customer's site in parallel with their SM, and one PQM was connected at the substation of the test area. Four customers among the twelve customers were selected to install the PQMs after studying their energy consumption history and fuse ratings. All twelve SMs in the area were switched during the test and the PQ was monitored during the disconnection and the reconnection of the SMs. All twelve SMs of the area were communicating with single MCU which was located at a substation nearby the test area named as Substation 2 in Figure 9.

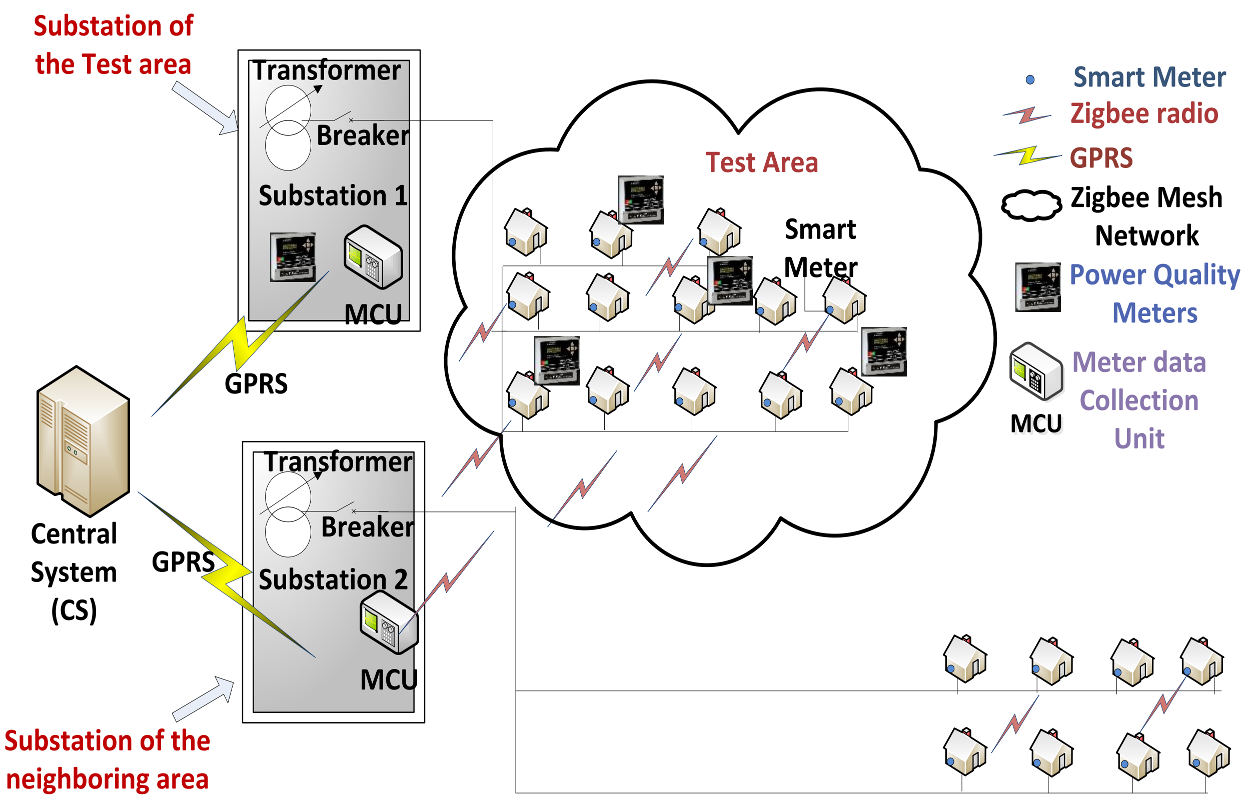


Figure 9: Test 1 Scenario of remote SM switching

3.6.2 Test 2 Scenario

Test 2 was carried out in an area during autumn period where thirty-seven residential customers were connected to a transformer of 800 kVA rating. The fuse ratings of the customers were between 16 A to 35 A. All customers of this area also had three phase power supply. Similar to the Test 1, four PQMs were connected temporarily at the four selected customer's site, and one PQM was connected at the substation of the selected area. Four customers were selected to install the PQMs after studying their energy consumption history and fuse rating. Because, high current flow through the PQM gives better PQ measurement compared to low current flow through the PQM. The PQ was not measured at the remaining thirty-three customers by the PQMs. These thirty-three SMs and also the four selected SMs with the four PQMs were switched during the test. The PQ was monitored during the test period of the SMs switching. The MCUs are usually located at the substations but it can also be located in the cable box as shown in Figure 10. The Figure also shows that four MCUs were communicating with the selected thirty-seven SMs of the test area. Different MCU was communicating with different SMs and also the number of SMs under each MCU was different during the test.

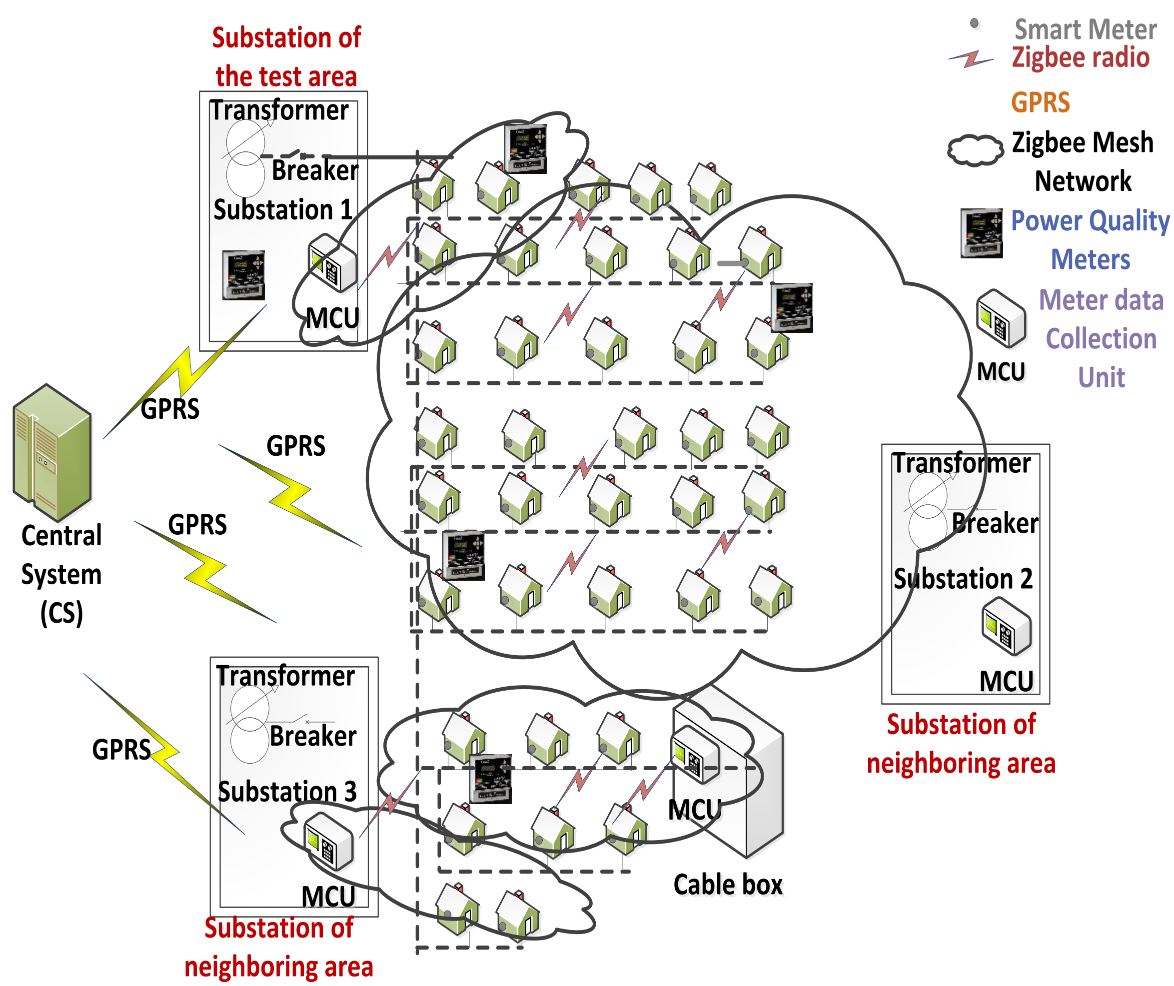


Figure 10: Test 2 Scenario of remote SM switching

3.6.3 Test 3 Scenario

Test 3 was conducted in a residential area during winter period when the load typically is high and the temperature is very low. In the test area, 177 customers were connected to a transformer of 800 kVA rating. In the test area, some of the SMs were located outside which are easily accessible. However, some of the SMs were located inside the apartment which are not easily accessible in case of emergency replacement of SM. Eighty-eight customers were selected from the test area for the SMs switching test after checking easy physical accessibly to the SMs. The reason was to make sure that the DSO can replace any faulted SMs if necessary. Because, some SMs might take longer time to re-establish the communication network due to any problem in the communication network. All selected customers had three phase connections except for one customer who had single phase connection. The fuse ratings of the customers were below 63A.

Four customers out of these eighty-eight customers were selected to install PQMs at their premises for measuring the PQ during the test. Two customers were located near the substation and another two customers were located far from the substation. The idea was to switch two SMs (one near and one far from the substation) out of four SMs where PQMs were installed. The remaining two SMs with PQMs (one near and one far from the substation) were not switched remotely to investigate the impact of multiple SMs switching on these two customers. One PQM was also installed at the substation of the selected area to record the PQ data.

The test was performed during the planned outage period. First, the selected SMs (eighty-six customers out of eighty eight customers which were selected from total 177 customers) were remotely disconnected by switching the SMs. The remaining ninety-one customers in the area had power supply at this point of time. Then, the power supply of the selected area was completely interrupted from the substation of that area for the PM work. The reason for planned PM work was to step up the voltage of the transformer by using the tap-changer. The breaker of the substation was reconnected after stepping up the voltage. At this stage, the non-switched ninety-one customers immediately got power supply back. However, the eighty-six remotely switched customers did not have power supply back to their appliances at this stage. Finally, the SMs of the selected customers were reconnected remotely to return the power supply to the customer's load.

Figure 11 shows the scenario of the Test 3. The Figure shows that two PQMs were installed at the customers who are close to the substation and the other two PQMs were installed at the customers who are far from the substation.

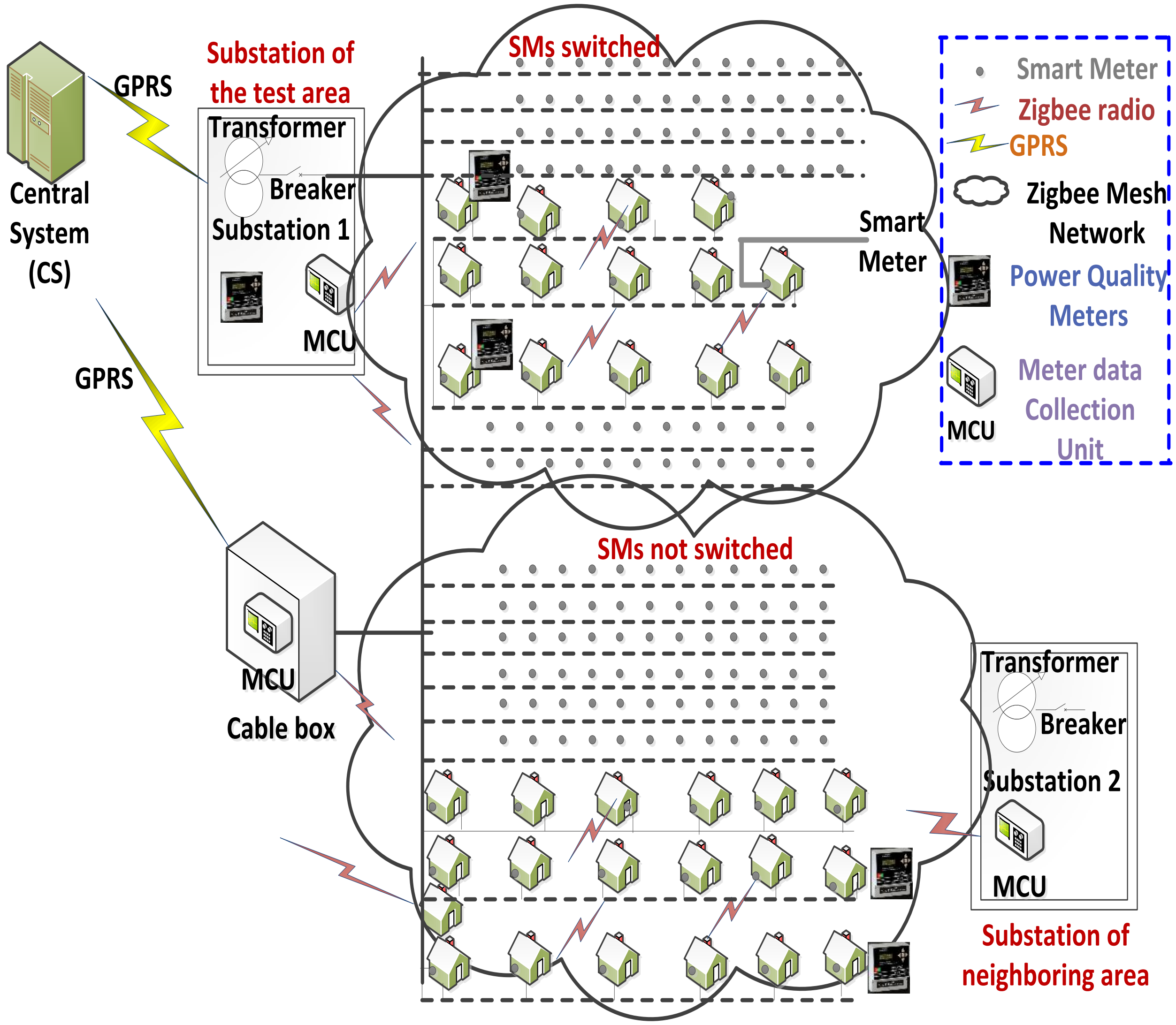


Figure 11: Test 3 Scenario of multiple SMs switching

Chapter 4 Test Results from multiple SMs switching

This chapter provides an overview of the tests results resulting from this thesis work using multiple SMs switching. The chapter begins with an introduction to the compiled data received from the PQMs, and the switching data from the CS during the tests. The time for disconnecting and reconnecting multiple SMs, and also the average voltages and currents are presented in this chapter for the period of SMs switching. Finally, the PQ events which were recorded in the PQMs are presented.

4.1 Voltage variations during multiple SMs switching

Five PQMs recorded the average phase voltages and phase currents with one-second time window during each of the three tests. The phase voltages and currents were measured at the customer level and also at the substation level. In this Section, the voltage variations are shown by comparing the voltage values of each phase before the SMs switching with the voltage values of each phase after the SMs switching. The variation in voltage is shown both at the customer level and the substation level for the three tests.

4.1.1 Voltage variations during the Test 1

The number of customers was twelve during the Test 1 and the transformer rating of the test area was 500 kVA. The voltage variations at the substation level and also at the customer level were not significant since the number of customers in the area was very low compared to the capacity of their respective transformer. The changes in phase voltages during SMsD of the Test 1 are shown in Table 6. The Table shows the phase voltages at the beginning of SMsD period and also at the end of the SMsD period. Moreover, the Table shows the changes in voltages for SMsD. The locations of the PQMs at the four customer levels are denoted as C11, C12, C13 and C14, where first digit after 'C' represents the test number and second digit represents the customer number. Moreover, the location of the PQM at the substation of the Test 1 is denoted as S1. The voltages at the three different phases are denoted as Ph1, Ph2 and Ph3.

Table 6: Change in phase voltages during SMsD of the Test 1

PQM location	**Before SMsD**			**After SMsD**			**Change in voltage for SMsD**		
	Ph1 (V)	**Ph2 (V)**	**Ph3 (V)**	**Ph1 (V)**	**Ph2 (V)**	**Ph3 (V)**	**Ph1 (V)**	**Ph2 (V)**	**Ph3 (V)**
Sub-Station, S1	235.7	235.6	236.8	235.9	235.6	236.9	0.2	0	0.1
C11	235.6	235.3	236.8	236.1	235.8	237.0	0.5	0.5	0.2
C12	235.8	235.5	236.7	236.1	235.8	237.0	0.3	0.3	0.3
C13	234.9	234.5	236.2	236.0	235.7	236.9	1.1	1.2	0.7
C14	234.6	235.9	236.9	235.9	236.2	236.4	1.3	0.3	0.5

The voltage at the substation was stepped down by using the tap changer of the transformer according to the plan of PM work. For this reason, the voltage values are seen decreased during the SMsR. Table 7 shows the changes in phase voltages during SMsR of the Test 1. The Table shows the phase voltages before and after the SMsR period and also the changes in voltage for SMsR. It can be seen here that phase 1 voltage of the customer C14 decreased by 8.6 V. The reason is that the customer was taking almost 30 A current on that phase after reconnection of the associated SM.

Table 7: Change in phase voltages during SMsR of the Test 1

PQM location	Before SMsR			After SMsR			Change in voltage for SMsR		
	Ph1 (V)	Ph2 (V)	Ph3 (V)	Ph1 (V)	Ph2 (V)	Ph3 (V)	Ph1 (V)	Ph2 (V)	Ph3 (V)
Sub-Station, S1	230.5	230.3	231.4	230.1	230.1	231.1	-0.4	-0.2	-0.3
C11	230.8	230.6	231.6	229.5	228.9	230.9	-1.3	-1.7	-0.7
C12	230.8	230.5	231.6	228.1	230.6	229.5	-2.7	0.1	-2.1
C13	230.7	230.5	231.5	228.2	227.9	229.7	-2.5	-2.6	-1.8
C14	230.8	230.5	231.6	222.2	231.6	231.5	-8.6	1.1	-0.1

4.1.2 Voltage variations during the Test 2

The number of customers was thirty-seven during the Test 2 and the transformer rating of the test area was 800 kVA. The number of customers during the Test 2 was higher than the number of customers during the Test 1. However, the power rating of the transformer was also higher in the Test 2 compared to transformer of the Test 1. For this reason, expectation of significant voltage change was low during the Test 2. The measured phase voltages of the Test 2 are shown in Table 8. The Table shows the voltages at the beginning of SMsD and also the voltages at the end of SMsD. Moreover, the changes in voltages due to SMsD are shown in the Table. The locations of the PQMs at the four customer levels are denoted at C21, C22, C23 and C24, where first digit after 'C' represents the test number and second digit represents the customer number. Moreover, the location of the PQM at the substation of the Test 2 is denoted as S2.

Table 8: Change in phase voltages during SMsD of the Test 2

PQM location	Before SMsD			After SMsD			Change in voltage for SMsD		
	Ph1 (V)	Ph2 (V)	Ph3 (V)	Ph1 (V)	Ph2 (V)	Ph3 (V)	Ph1 (V)	Ph2 (V)	Ph3 (V)
Sub-Station, S2	238.8	238.4	240.3	239.5	239.3	240.8	0.7	0.9	0.5
C21	238.5	238.4	240.3	239.5	239.2	240.7	1.0	0.8	0.4
C22	238.3	240.1	238.7	239.4	240.9	239.6	1.1	0.8	0.9
C23	238.2	238.3	240.0	239.9	239.4	240.9	1.7	1.1	0.9
C24	239.3	237.9	240.0	239.6	239.4	240.8	0.3	1.5	0.8

The voltage at the substation was stepped down by using the tap changer of the transformer according to the plan of PM work. For this reason, the voltage values before the SMsR are seen generally decreased compared to the voltage values after the SMsD. Table 9 shows the changes in phase voltages during SMsR of the Test 2. The Table shows the phase voltages before and after the SMsR period and also the changes in voltage for SMsR. It can be seen here that the voltage at the substation increased after completing the SMsR. But, by analyzing the voltage data at the substation, it is found that the voltage had been fluctuating during the period of SMsR. The reason of the fluctuation could be that the voltage change at the upstream grid influenced the voltage at the substation of the test area. The fluctuation of the voltage at the substation was observed in a similar way in all three phases throughout the SMsR period. Moreover, the voltages at C24 are seen to be increased on phase 1 and phase 3. By analyzing the voltage data at C24 for the whole SMsR period, it was found that C24 was connected almost at the last moment of the SMsR period and the voltages on each phase were actually decreased after the load reconnection. But, since the voltages at C24 fluctuated in a similar way as the voltage fluctuation of the substation, the voltages were found higher just before reconnection of the SM. For this reason, the change in the voltages at the C24 was found positive i.e., increased although the voltage decreased due to connection of loads.

Table 9: Change in phase voltages during SMsR of the Test 2

PQM location	**Before SMsR**			**After SMsR**			**Change in voltage for SMsR**		
	Ph1 (V)	**Ph2 (V)**	**Ph3 (V)**	**Ph1 (V)**	**Ph2 (V)**	**Ph3 (V)**	**Ph1 (V)**	**Ph2 (V)**	**Ph3 (V)**
Sub-Station, S2	231.0	230.8	232.2	231.7	230.9	233.0	0.7	0.1	0.8
C21	231.3	230.7	232.3	230.1	229.3	231.3	-1.2	-1.4	-1.0
C22	231.0	232.5	231.4	229.5	231.4	230.1	-1.5	-1.1	-1.3
C23	231.5	230.9	232.4	230.5	230.0	231.2	-1.0	-0.9	-1.2
C24	231.0	230.7	232.1	232.0	230.4	232.6	1.0	-0.3	0.5

4.1.3 Voltage variations during the Test 3

The voltage variations for the SMs switching during the Test 3 are shown in Table10. The number of customers in the area of the Test 3 was much higher compared to the first two tests. Almost fifty percent of the SMs were switched during the test and the number of switched customers is still much higher than the customers switched in the first two tests. The power rating of the transformer of this area was however 800 kVA, which is similar to the transformer rating of the Test 2. The Table shows the phase voltages at the beginning of SMsD period and also at the end of the SMsD period. Moreover, the Table shows the changes in voltages for the SMsD. The voltage values are one-second average values recorded in the five PQMs. The locations of the PQMs at the four customer levels are denoted at C31, C32, C33 and C34, where first digit after ‘C’ represents the test number and second digit represents the customer number. Moreover, the location of the PQM at the substation of the Test 3 is denoted as S3. It is seen that the phase voltages of the substation increased by around 1 V after the SMsD. By analyzing the voltage measurements during the SMsD period, it is seen that the voltages at the four customer level were varied following the variation of the substation voltage and also with the changes in the load current of the respective customer. Moreover, at some customer level the phase 3 voltages are seen to be higher than the phase 3 voltage of the substation. The reason could be that as the load currents on phase 3 of the customers were very low, the capacitive effect of the underground cable was dominant which caused the increase in voltage on the other end of the underground cable. However, the voltage variations were found within the acceptable limit.

Table 10: Change in phase voltages during SMsD of the Test 3

PQM location	**Before SMsD**			**After SMsD**			**Change in voltage for SMsD**		
	Ph1 (V)	**Ph2 (V)**	**Ph3 (V)**	**Ph1 (V)**	**Ph2 (V)**	**Ph3 (V)**	**Ph1 (V)**	**Ph2 (V)**	**Ph3 (V)**
Sub-Station, S3	235.0	233.3	233.7	235.8	234.5	234.4	0.8	1.2	0.7
C31	231.7	231.9	235.2	234.3	234.2	235.6	2.6	2.3	0.4
C32	228.3	229.3	232.2	232.2	232.8	234.6	3.9	3.5	2.4
C33	231.9	232.7	234.7	233.9	234.1	235.5	2	1.4	0.8
C34	228.5	226.5	234.1	231.4	233.1	234.3	2.9	6.6	0.2

The voltage at the substation was not stepped down by the tap changer during the Test 3 as it was done during the first two tests. Table 11 shows the changes in phase voltages during SMsR of the Test 3. The Table shows the phase voltages before and after the SMsR period and also the changes in voltage for SMsR. The voltage values shown in the Table are one-second average value. It is seen here that the voltage variations at the four customer level and also at the substation level were also within the acceptable limit for the SMsR.

Table 11: Change in phase voltages during SMsR of the Test 3

PQM location	**Before SMsR**			**After SMsR**			**Change in voltage for SMsR**		
	Ph1 (V)	**Ph2 (V)**	**Ph3 (V)**	**Ph1 (V)**	**Ph2 (V)**	**Ph3 (V)**	**Ph1 (V)**	**Ph2 (V)**	**Ph3 (V)**
Sub-Station, S3	236.7	235.7	235.1	236.0	235.1	234.7	-0.7	-0.6	-0.4
C31	235.6	234.9	236.5	235.2	234.9	236.1	-0.4	0	-0.4
C32	232.3	234.0	234.8	232.4	233.4	235.0	0.1	-0.6	0.2
C33	234.9	234.6	236.4	234.3	234.1	236.6	-0.6	-0.5	0.2
C34	226.8	235.4	235.6	229.6	231.6	233.4	2.8	-3.8	-2.2

4.2 Power Quality events recorded during SMs switching

The PQMs recorded waveform data for the triggered PQ events. All PQ events recorded in the PQM were not related to the SMs switching e.g., the PQMs recorded some voltage sag/swell events or transient events when the PQMs were removed from the monitoring location. The long interrupt events were recorded when the substation was disconnected for PM work and the events are marked with orange color. The events that were recorded during the SMs switching are marked with red color and the events recorded during disconnection of the PQMs from the monitoring locations are marked with green color. Moreover, some events were recorded during the substation power disconnection in addition to long interrupt events and those events are marked with blue color. Table 12 shows numbers different PQ events recorded during the test period of the Test 1.

Table 12: PQ events recorded during the Test 1

PQM location	Long Interrupt	Voltage Sag	Voltage Swell	Transient
Substation, S1	***1***	***0***	***0***	***0***
C11	***1***	***0***	***1***	***0***
C12	***1***	***0***	***0***	***0***
C13	***1***	***0***	***0***	***0***
C14	***1***	***1***	***0***	***1***

Table 13 shows numbers of PQ events recorded during the test period of the Test 2. The PQM at the customer 3 location recorded two long interrupt events. One long interruption event was recorded for the disconnection of the substation and another long interrupt was recorded for the period of PQM disconnection from the monitoring location until the PQM was connected to download the recorded data to a computer. It is seen here that three transient events were recorded at customer 3 and one transient event was recorded at customer 4 during the SMs switching. But, two of the four transient events are seen as events from measurement noise. Finally, two transient events are seen related to the SMs switching and the events were recorded during reconnection of the two SMs.

Table 13: PQ events recorded during the Test 2

PQM location	Long Interrupt	Voltage Sag	Voltage Swell	Transient
Substation, S2	***1***	***3***	***0***	***0***
C21	***1***	***0***	***1***	***0***
C22	***1***	***1***	***1***	***1+3***
C23	***1 + 1***	***0***	***1***	***0***
C24	***1***	***0***	***0***	***1+1***

Table 14 shows numbers of PQ events recorded during the test period of the Test 3. It is seen here that three, five and four transient events were recorded during the period of SMs switching at the customer 2, customer 3 and customer 4 respectively. The transient events were found during the reconnection of the SMs.

Table 14: PQ events recorded during the Test 3

PQM location	Long	Voltage Sag	Voltage Swell	Transient
Substation, S3	***1***	***0***	***0***	***1***
C31	***1***	***0***	***0***	***1***
C32	***1***	***0***	***0***	***3+3***
C33	***1***	***1***	***0***	***1+1+5***
C34	***1***	***0***	***1***	***1+1+4***

4.3 Status update of the SMs switching from the central system

A command with a list of selected SMs to be disconnected or reconnected was sent remotely from the CS to the selected MCUs during the tests. The MCUs were sending back the status update of the SMs switching to the CS on real time while executing the SMs switching. The status update report shows the time instants when the MCUs started disconnecting or reconnecting SMs and also the confirmation of disconnections and reconnections of the SMs. Moreover, the report shows the timing for the SMs which were failed to disconnect or reconnect. The status update reports were collected from the CS during each test to identify the time required to disconnect/reconnect each SM and also to analyze the test data. The MCUs start disconnecting or reconnecting SMs one by one and try all SMs once in the first attempt. In the second attempt, the MCUs try the failed SMs to switch again and again until it becomes successful to switch or until the switching command is cancelled. The status update report also helps to identify after how many attempts the failed SMs successfully got connected.

4.4 Error in the SMs status update reports

This thesis work analyzed the status update reports of SMs disconnection and reconnection which were collected from the CS and identified the actual instants of each SM switching. Since, the MCUs send real time status of SMs switching to the CS, it is important that the report should be reliable. Otherwise, wrong information might lead to take unnecessary actions by the DSO e.g., replacing the SM, which is reported as failed to reconnect. This thesis work found some error in the status update report of each test e.g., wrong update about successful disconnect/connect of the SMs, showing different update for the same SM at different attempts of the same switching signal, multiple status update for same SM.

During the tests, the reports were showing that some of the SMs were failed to disconnect or reconnect. However, after investigating each failed SM individually, this thesis work found that some of them were actually disconnected or reconnected. Each failed SM was investigated by asking real time data from the SMs. It was found that some of the SMs were showing real time voltages and currents, which indicates an error in the report. Moreover, in the status update report of the Test 3 it was observed that some of the SMs, which were successfully connected in the first attempt, are shown as failed in the second attempt of reconnection. The percentage of this type of error in the status update report of the Test 3 was 27.6%.

Furthermore, in the status update report of the Test 2 it was observed that two SMs were tried to reconnect two times and reported as connected both times. It is seen that same SM received reconnect command from two MCUs. This kind of error could lead to confusion in the data analysis. Percentage of this kind of error was 5.4%. Moreover, it was observed that same SM received reconnect signals from two MCUs and both MCUs reported failure to reconnect almost at the same time.

Table 15 shows a summary of the percentage of error of this type in the status update reports. The Table shows percentage of errors for one type of error where a SM which was actually disconnected/connected but the report shows that SM was failed to disconnect/connect.

Table 15: Percentage of error found in the Status update report

	Percentage of Error during the Test 1	**Percentage of Error during the Test 2**	**Percentage of Error during the Test 3**
Error in SMs status update during SMsD	8.3%	18.4 %	2.33%
Error in SMs status update during SMsR	8.3%	18.4 %	4.65 %

4.5 Time required for disconnecting/connecting multiple SMs

4.5.1 Time steps of the Test 1

The time periods for the SMsD and the SMsR and also the time instants of the substation switching are presented in Figure 12. As seen here, the disconnection process of twelve selected SMs required ninety six seconds while the reconnection process of the SMs required one hundred and twenty seven seconds which was expected for the SMs switching.

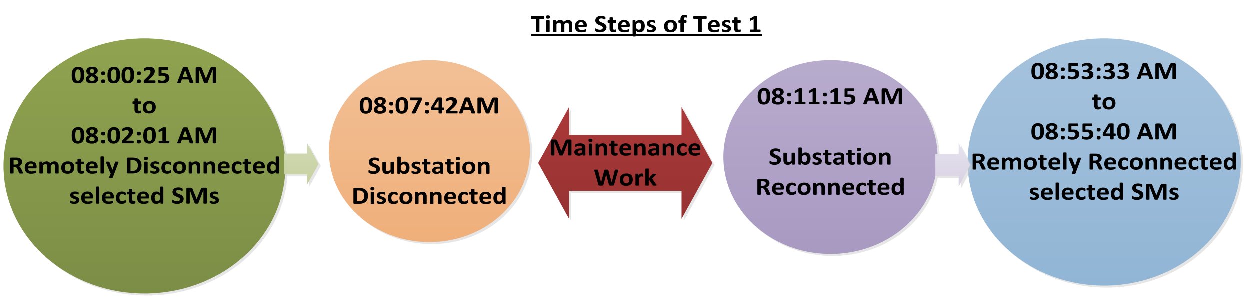


Figure 12: Time instants of SM switching during the Test 1

4.5.2 Time steps of the Test 2

The time steps for the Test 2 are presented in Figure 13. As seen here, the disconnection process of thirty-seven selected SMs required two hundred twenty four seconds while the reconnection process of the SMs required two hundred twenty five seconds.

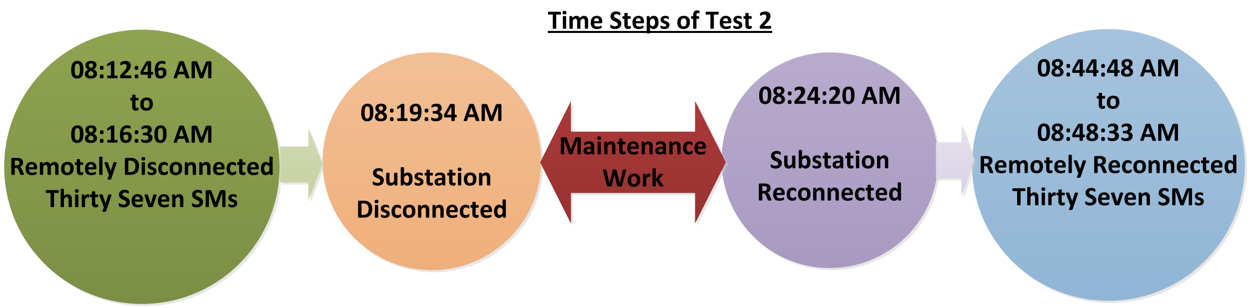


Figure 13: Time instants of SM switching During the Test 2

4.5.3 Time steps of the Test 3

The time steps for the Test 3 are presented in Figure 14. As seen here, the disconnection process of eighty-four selected SMs required three hundred thirty seconds. But, due to communication problem two SMs were failed to disconnect. On the other hand, the reconnection of the SMs required longer time than the test period. Because, some of the SMs took longer time to join the ZigBee network. Several attempts were needed to reconnect the SMs. In the first attempt of reconnection, forty-six SMs were reconnected and it took eighteen minutes eight seconds. In the next attempt of eleven minutes and fifty seconds, five SMs were reconnected. The third attempt for the duration of twenty-eight minutes and thirty-eight seconds was not successful to connect any SM of the remaining thirty-five SMs. But the fourth attempt was successful to connect twenty-five SMs and the duration of the attempt was twenty-seven minutes and sixteen seconds. Moreover, in the next fifty-seven minutes of the last attempt, only one SM was successfully connected. Finally, nine SMs were left to reconnect remotely which were reconnected manually by using optical eye. Optical eye can be used to reconnect SM manually if the SM does not respond to remote signal. But, this technique can be applied for a certain type of SM. Because, other types of SMs do not support optical eye technique for manual reconnection of SM. If any SM, which does not support the optical eye solution, fails to respond to the remote switching signal, replacing the SM would be a solution for these types of SMs.

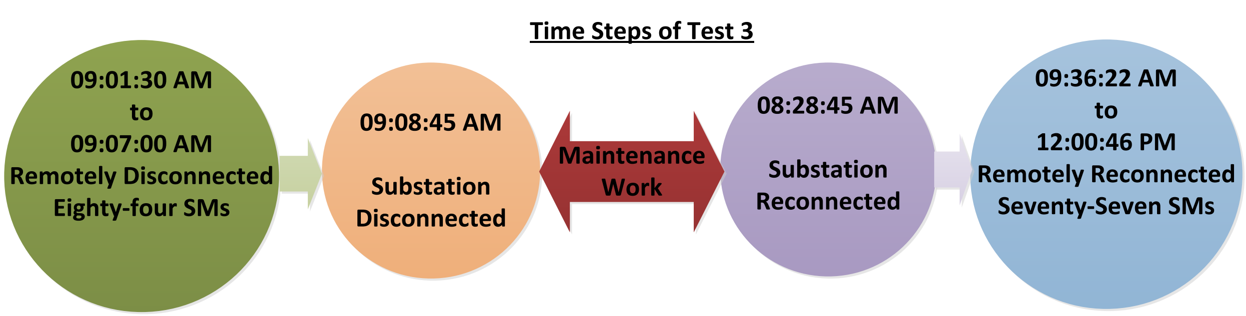


Figure 14: Time instants of SM switching During the Test 3

4.5.4 Comparison of SMs switching time

This thesis work identified the time required to disconnect and reconnect the SMs from the status update reports. Most of the SMs were disconnected at first disconnection attempt but few of them were disconnected after multiple attempts. Similarly, most of the SMs were reconnected at first reconnection attempt but few of them were reconnected after multiple attempts. However, in the Test 3 reconnection of the SMs were mostly unsuccessful in the first attempt. Because, the SMs took time to get connected in the ZigBee network and during that time period, the SMs were not available for communication. Moreover, there is one kind of SM which requires two steps to connect the SM. First, it needs to activate the switch and after that it connects the switch in the next step. This specific type of SM takes more time to reconnect compared to the reconnection time required for other types of SMs. However, the disconnection process needs only one step for all types of SMs. Table 16 shows the total time required for disconnection and reconnection of the SMs during the tests and also shows the average time required to switch individual SM. The time presented in this Table is in second. Only the successfully disconnected or connected SMs are considered for SM switching time calculation. The SMs which were failed to switch or switched but after several attempts are not considered in the time calculation. It is seen here that reconnection process of the Test 3 took longer time. The reason is that out of 77 successfully reconnected SMs there were 57 SMs which requires two steps for reconnection. However, there was only one SM of this kind during the first two tests.

Table 16: Time required for disconnecting and reconnecting SMs

	Number of disconnected SM	Time required for SM Disconnection		Number of reconnected SM	Time required for SM Reconnection	
		Total time (sec)	Average time (sec)		Total time (sec)	Average time (sec)
Test 1	12	96	8	12	127	10.6
Test 2	37	216	5.8	37	210	5.7
Test 3	84	639	7.6	77	942	12.2

4.6 Switching technique of the MCUs

The status update reports show that the MCUs of the investigated system disconnected or reconnected the SMs one by one. In the Test 1, there was only one MCU and the MCU switched all SMs one by one. But in the Test 2 and the Test 3, there were four and three MCUs respectively. During the Test 2, the thirty-seven switched customers were found divided under four MCUs as 27 SMs, 5 SMs, 2 SMs and 3 SMs respectively. During the Test 3, the eighty-six switched customers were found divided under three MCUs as 41 SMs, 44 SMs and 1 SM respectively. All MCUs switches SMs in parallel after receiving switching command from the CS. Moreover, the MCUs send the confirmation report to the CS in parallel. It is also seen that the MCUs start executing the next switching almost instantly after completing the previous switching. Table 17 shows an example of parallel switching execution of multiple MCUs from the Test 2. The Table also shows the execution of multiple SMs switching for individual MCU. However, for MCU 1, switching executions are shown only the first ten SMs out of twenty-seven SMs. The time instants marked with violet colors indicate the starting time of reconnections and the time instants marked with orange colors indicate the confirmation time instants of the reconnections. Moreover, the time required for reconnecting each SM which is named as SMR time is shown in second (s) with black colored numbers in the Table.

Table 17: Switching techniques of the MCUs during the Test 2

SM Sl.	MCU 1			MCU 2			MCU 3			MCU 4		
	Reconnection Started	Reconnection Confirmed	SMR Time	Reconnection Started	Reconnection Confirmed	SMR Time	Reconnection Started	Reconnection Confirmed	SMR Time	Reconnection Started	Reconnection Confirmed	SMR Time
1.	08:44:54,913	08:45:05,372	10s	08:44:56,319	08:45:06,858	10s	08:44:56,124	08:45:03,984	7s	08:44:56,147	08:45:06,704	10s
2.	08:45:05,373	08:45:13,280	8s	08:45:06,858	08:45:17,299	11s	08:45:03,985	08:45:11,804	8s	08:45:06,704	08:45:14,465	8s
3.	08:45:13,280	08:45:20,990	7s	08:45:17,299	08:45:25,286	8s				08:45:14,465	08:45:22,226	8s
4.	08:45:20,991	08:45:28,682	8s	08:45:25,286	08:45:33,097	8s						
5.	08:45:28,682	08:45:36,231	8s	08:45:33,097	08:45:40,905	7s						
6.	08:45:36,232	08:45:43,880	7s									
7.	08:45:43,881	08:45:51,650	8s									
8.	08:45:51,651	08:45:59,599	8s									
9	08:45:59,599	08:46:07,588	8s									
10	08:46:07,589	08:46:15,339	8s									

Chapter 5 Power Quality analysis of the test result

This chapter provides an analysis of the test result with respect to voltage quality variation and the PQ events. The maximum values of Ub (%), flicker and THD recorded during the SMs switching are compared with the corresponding values during normal operation. Moreover, the transient events recorded during the SMs switching are analyzed. Finally, the overall impact of SMs switching on the existing system is presented.

5.1 Voltage Quality variations

Regulators of voltage quality provide a number of conditions that the voltage characteristics have to fulfill for the voltage quality to be of sufficient. In the regulation, limits are given for the voltage-quality variations such as unbalance, THD and voltage fluctuations [51- 52].

5.1.1 Voltage Unbalance (Ub %)

The five PQMs that were used during each of the test, recorded the Ub (%) data. The Ub (%) data at the customer level were recorded in the four PQMs with ten-minute data interval during the Test 1 and the Test 2. However, the Ub (%) data at the substation level was recorded with one-minute data interval during the first two tests in order to get more data at the substation level. For the voltage quality to be considered sufficient, all ten-minute values of the Ub (%) are required to be less than 2% for all voltage levels. Table 18 shows the maximum values of Ub (%) during the switching period of the SMs and also during the normal power supply condition to compare the values of Ub (%). As seen here, all ten-minute values of the Ub (%) during the SMs switching period both at the substation level and at the customer level are clearly below 2% for the first two tests. By comparing the Ub (%) values during the SMs switching with the Ub (%) values during normal power supply period, it can be said that the Ub (%) did not get additional impact due to the SMs switching.

Table 18: Maximum values of Voltage unbalance Ub (%) during the first two Tests

	Test 1					**Test 2**				
Location of PQMs	*C11*	*C12*	*C13*	*C14*	*S1*	*C21*	*C22*	*C23*	*C24*	*S2*
Max Ub% during Switching	0.38	0.35	0.37	0.59	0.34	0.43	0.43	0.44	0.43	0.44
Max Ub% in normal period	0.38	0.37	0.38	0.54	0.38	0.43	0.44	0.46	0.43	0.41

During the Test 3, the Ub (%) values were recorded with one-second data interval both at the substation level and also at the four customer level. Table 19 shows the maximum Ub (%) values at the selected customers and substation level during the Test 3. As seen here, the Ub (%) values were less than 1% during the SMsD and the SMsR. By comparing the Ub (%) values during SMs switching with the Ub (%) values during normal operation period, it can be said that the Ub (%) was not affected by SMs switching.

Table 19: Maximum values of Voltage unbalance Ub (%) during the Test 3

	Test 3				
Location of PQMs	***C31***	***C32***	***C33***	***C34***	***S3***
Max Ub (%) during SMs switching	0.70	0.61	0.56	0.83	0.47
Max Ub (%) in normal operation period	0.77	0.67	0.60	0.86	0.53

5.1.2 Flicker

Flicker is the effect produced on the visual human perception by a changing emission of light by lamps subjected to fluctuations of their supply voltage. The severity of the disturbance is described by two parameters, the short-term flicker severity (Pst), and the long-term flicker severity (Plt). The EN 50160 gives an indication only for the Plt parameter which is a standard for 60W incandescent lamp. According to EN 50160, 95% of the Plt values should be below 1.0 in one week measurement period. During the first two tests, the Pst values were recorded with ten-minute data interval. Table 20 shows the maximum values of Pst among the Pst values recorded in the PQMs during the SMs switching of the first two tests. The Table also shows the maximum values of Pst among the Pst values recorded in the PQMs during normal operation of the first two tests. As seen here, the maximum values of ten-minute Pst values are below 1.0 both at the customer level and also at the substation level. By comparing the Pst values during the SMs switching with the Pst values during normal power supply period, it can be said that the flicker level did not get additional impact due to multiple SMs switching.

Table 20: Maximum values of Pst during the first two tests

	Test 1					**Test 2**				
Location of PQMs	*C11*	*C12*	*C13*	*C14*	*S1*	*C21*	*C22*	*C23*	*C24*	*S2*
Max Pst during Switching	0.27	0.16	0.18	0.62	0.13	0.13	0.15	0.16	0.09	0.08
Max Pst in normal period	0.16	0.14	0.16	0.36	0.16	0.10	0.10	0.19	0.10	0.10

The Pst values were recorded with one-second data interval during the Test 3 both at the substation level and also at the customer level. Table 21 shows the maximum values among the one-second Pst values recorded during the SMs switching period and also during the normal operation period of the Test 3. The Table also shows how many times one-second Pst values reached values higher than 1.0 during the SMs switching period and also during normal operation period. As seen here, one-second Pst with values higher than 1.0 were observed at some customer level during SMs switching. However, the calculated 1-min average values of Pst showed that all Pst values were below the limit of 1.0. Similarly, one-second Pst with values higher than 1.0 were also observed at some customer level and at the substation level during the normal operation period. The calculated 1-min average values of Pst during normal operation period also shows that all Pst values were below 1.0. By comparing the Pst values of the Test 3 during the SMs switching period and the normal operation period, it can be said that flicker level was not impacted due to multiple SMs switching.

Table 21: Maximum values of Pst during the Test 3

	Test 3				
Location of PQMs	***C31***	***C32***	***C33***	***C34***	***S3***
Max Pst during Switching	1.11	1.74	0.74	3.87	0.37
Number of times 1-sec Pst values reached higher than 1.0 during SMs switching	6	4	0	7	0
Max Pst in normal period	2.25	0.85	1.69	3.78	2.28
Number of times 1-sec Pst values reached higher than 1.0 during normal operation	136	0	4	6	7

5.1.3 Harmonics

The PQMs measured the individual harmonic contents and expressed the output with reference to the fundamental component of the voltage, indicating the THD factor in percent. The THD (%) values were recorded with one-second data interval during the three tests. According to EN 50160, the THD values in percent should be less than 8% on a LV grid [52]. Table 22 shows the maximum values of THD (%) during the first two tests. As seen here, the THD (%) values were much lower than the limit of 8% during the SMs switching period and also during the normal operation period. By comparing the THD (%) values during the SMs switching period with the THD (%) values during the normal operation period, it can be said that the SMs switching did not affect the THD (%) at LV level.

Table 22: Maximum values of THD (%) during the first two tests

	Test 1					Test 2				
Location of PQMs	*C11*	*C12*	*C13*	*C14*	*S1*	*C21*	*C22*	*C23*	*C24*	*S2*
Max THD% during SMs switching	1.16	1.17	1.17	1.29	1.21	1.32	1.32	1.30	1.32	1.22
Max THD% during normal operation period	1.29	1.26	1.27	1.38	1.26	1.30	1.43	1.44	1.43	1.28

Table 23 shows the maximum values of THD (%) of the Test 3 during the SMs switching period and also during the normal operation period. As seen here, the THD (%) values were much lower than the limit of 8% during the SMs switching period and also during the normal operation period. By comparing the THD (%) values during the SMs switching period with the THD (%) values during the normal operation period, it can be said that the SMs switching did not affect the THD (%) at LV level.

Table 23: Maximum values of THD (%) during the Test 3

	Test 3				
Location of PQMs	***C31***	***C32***	***C33***	***C34***	***S3***
Max THD(%) during SMs switching	1.35	1.73	1.72	1.68	1.19
Max THD(%) in normal operation period	2.72	1.74	2.82	1.75	2.70

5.2 Power Quality Events

The characteristic of an event can be determined by using triggering method when an event is detected [54- 55]. The voltage quality is regulated based on the defined limits for voltage quality events such as voltage sag, voltage swells and rapid voltage changes [47]. The PQMs were configured to trigger the following events.

5.2.1 Voltage Sag

The voltage sag is defined as an event during which the one cycle rms voltage suddenly drops below 90% of the nominal voltage, followed by a return to a value higher than 90% of nominal value, in a time varying from 10 ms to 60 s [56]. The PQMs were set to trigger the voltage sag event based on the EN 50160 standard. The results from the three tests show that not a single voltage sag event was recorded in the PQMs during the multiple SMs switching.

5.2.2 Voltage Swell

The voltage swell is defined as an event during which the one cycle rms voltage suddenly exceeds 110% of the nominal voltage, followed by a return to a value lower than 110% of nominal value, in a time varying from 10 ms to 60 s. The PQMs were set to trigger the voltage swell event based on the EN 50160 standard. The results from the three tests show that not a single voltage swell event was recorded in the PQMs during the multiple SMs switching.

5.2.3 Rapid voltage changes

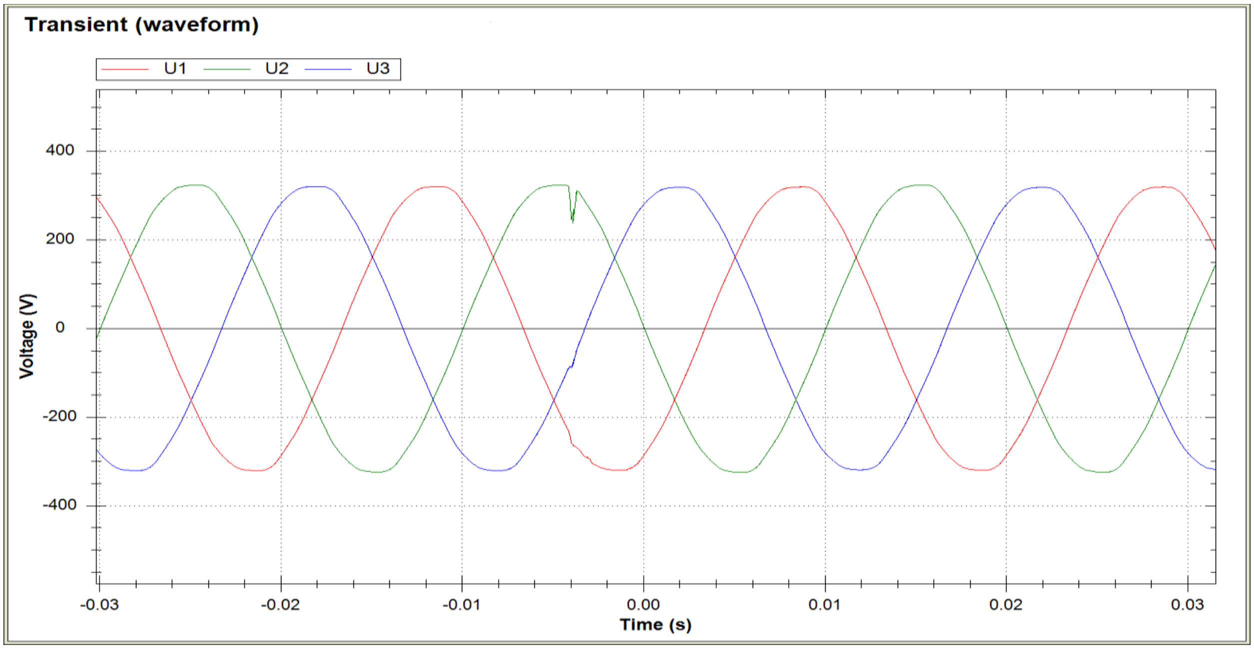
A rapid voltage change is defined as a change in rms voltage per second faster than 5% of the reference voltage [53]. According to the EN 50160 standard, typically rapid voltage changes do not exceed a depth of 5 % of the nominal voltage but higher depth up to 10% may occur occasionally. The test results show that there was no rapid voltage change event recorded in the PQMs during the SMs switching.

5.2.5 Voltage Transients

Voltage transients are also referred as voltage surges or voltage spikes or voltage impulses. A voltage transient shows up as brief and fast rising voltage excursions on the sine wave. They typically last for a few microseconds to several milliseconds. The spikes in voltage may vary in duration and magnitude. The electronic appliances used at homes and offices are designed to operate at a specified nominal voltage. Most equipment is designed to handle minor variations in their standard nominal operating voltage. However, if the transient is repetitive, the continual stressing may weaken sensitive electronics over time. A future transient with a low peak voltage event that would otherwise be safe could cause complete failure of a weakened component if circuit components become progressively weaker. Repeated small voltage transients may shorten the life of today’s computerized appliances and electronics

During the Test 2, Two transient events were recorded in two PQMs among the four PQMs. These two PQMs were installed at the two selected customer site. The transient events were recorded at the moment of the reconnections of the SMs associated with these two PQMs.

Figure 15 shows a voltage transient event recorded at a customer level during the Test 2. The Figure also shows the waveforms of the phase currents during the transient event. As seen here, the voltage transient event was recorded on phase 2 due to inrush current on the phase. The voltage on phase 2 suddenly dropped from 314 V to 237 V which represents a drop of 77 V and the voltage dropped in 0.16 milliseconds. The voltage drop was 33.5 % of the nominal voltage.



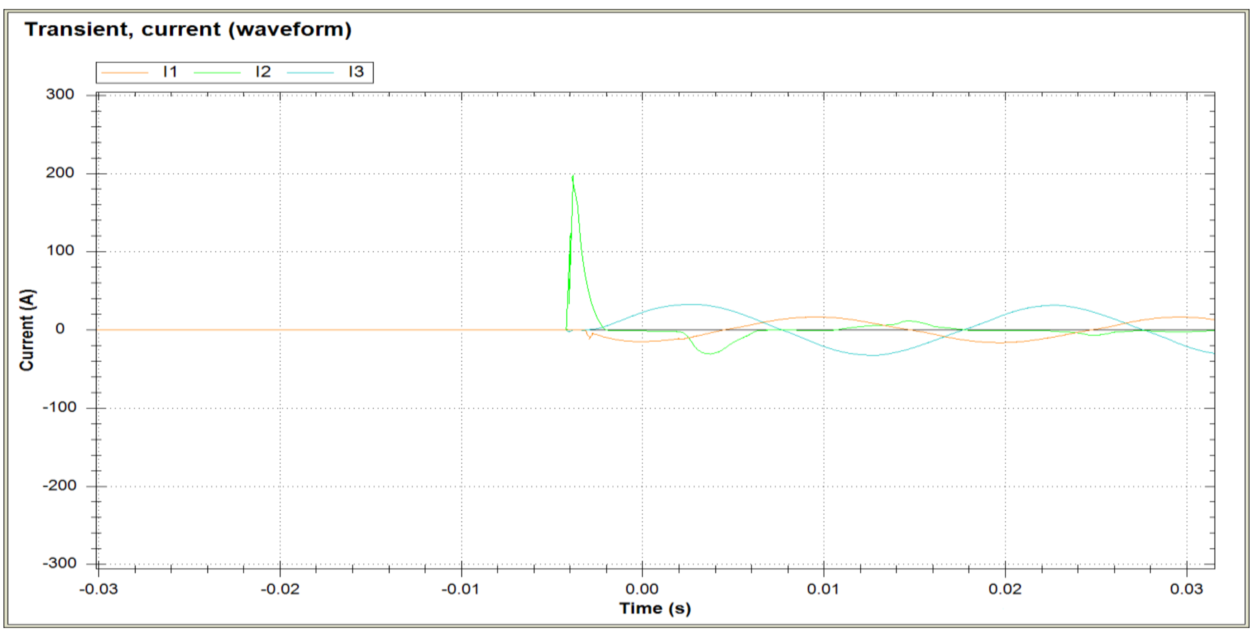


Figure 15: Currents and voltages of a voltage transient event recorded at customer C22 during the Test 2

Figure 16 shows a voltage transient event recorded at another customer level during the Test 2. The Figure also shows the waveforms of the phase currents during the transient event. This transient event was also recorded at the moment of the reconnections of the SMs associated with the PQMs. As seen here that the voltage transient event was recorded on phase 1 and phase 2 due to corresponding inrush current on phase 1 and phase 2. The voltage on phase 1 suddenly dropped from 313 V to 253 V which represents a drop of 60 V and the voltage dropped in 0.08 milliseconds. Again the phase 1 voltage increased from 253 V to 353 V in 0.08 milliseconds which represents a drop of 100 V. The voltage decrease was 26.1 % of the nominal voltage and voltage increase was 43.5 % of the nominal voltage respectively. Moreover, the voltage on phase 2 dropped from 230V to 122 V which is 47% of the nominal value.

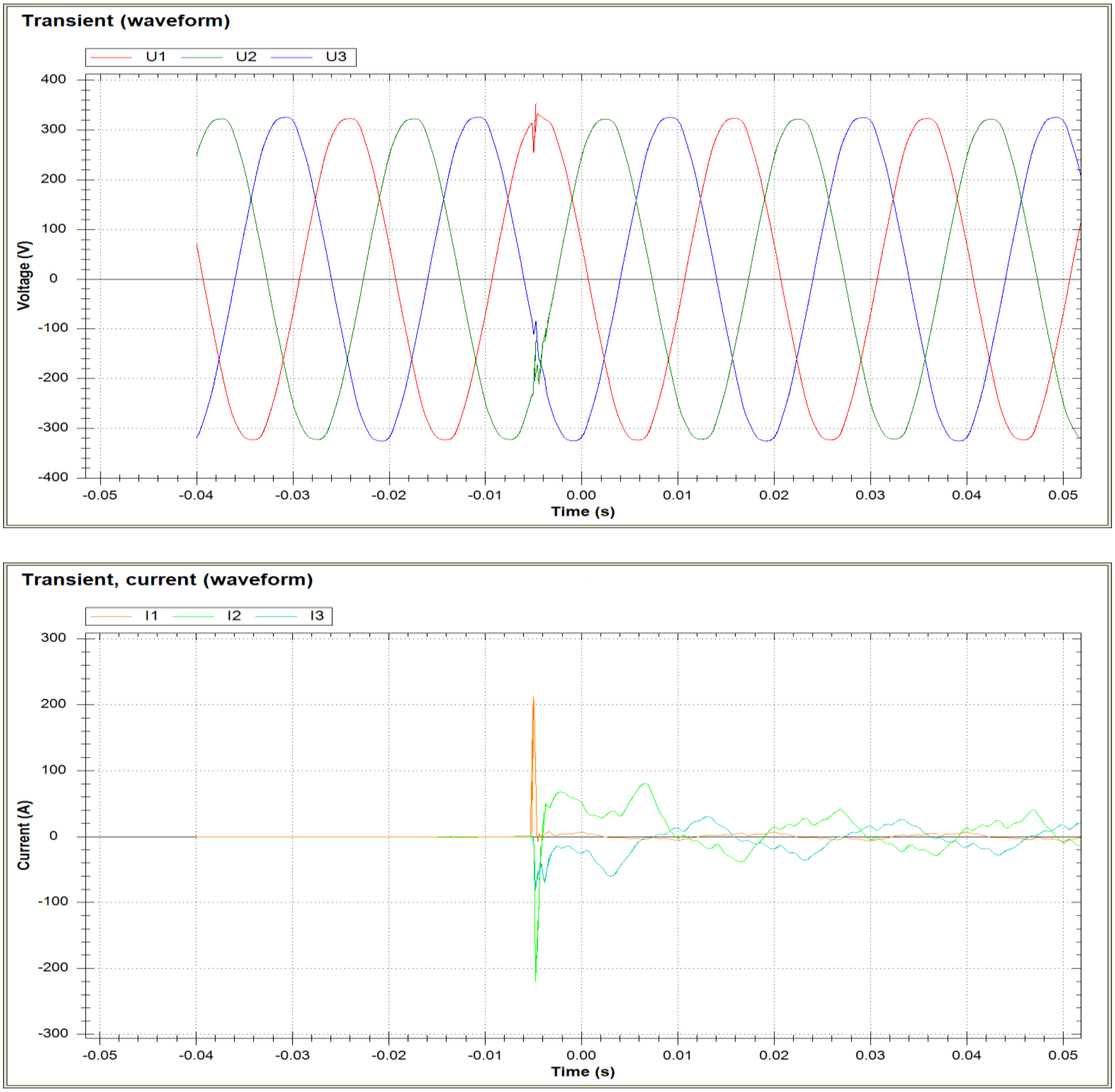


Figure 16: Currents and voltages of a voltage transient event recorded at customer C24 during the Test 2

The results from Test 3 show that fifteen transient events were recorded in the PQMs during the SMs switching. The events were recorded at customer level. Three PQMs out of four PQMs recorded the transient events at the customer level. The SMs associated with the four PQMs in the Test 3 were not switched in a similar way as it was done during the first two tests. The two SMs associated with two PQMs at customer C33 and C34 were not switched during the Test 3 and these two PQMs recorded nine transient events during the SMs switching. The test results also show that only one PQM, among the other two PQMs who's associated SMs were switched, recorded transient events and that PQM was located at C32.

The transient events recorded in the Test 3 have similarities in their nature e.g., all events were recorded at the moment of another SM reconnection during the Test 3. By comparing the SMs switching status update report and the moments of recorded transient events, it is seen that the transient events were recorded when SMs were reconnected. The reason could be that when a SM was reconnected, the load was taking inrush currents which caused a voltage transient and this voltage transient was propagated to the PQM which was monitoring the PQ at a customer site. Similarly other transient events may also be recorded when another SM was reconnected and the load of that customer were taking inrush current resulting voltage transients. The customers C32 and C34 are located far from the substation and close to each other. The test results from the PQMs of C32 and C34 show that when the PQM at C34 recorded a voltage transient event, the PQM at C32 also recorded a voltage transient event at approximately same time. Table 24 shows the time instants when the transient events were recorded in the PQMs of C32 and C34. As seen here the time differences are 1 sec which could be because of clock synchronization delay in the PQMs.

Table 24: The time instants of transient events recorded at C32 and C34 during Test 3.

PQ event (Voltage transient)	**C32 (Associated SM was reconnected at 09:44:31) Moment of Transient recorded**	**C34 (Associated SM was always ON) Moment of Transient recorded**	**Duration of the transient (millisecond)**	**Percentage of voltage change from the nominal value**
Transient 1	09:36:27	09:36:26	0.23	60%
Transient 2	09:38:53	09:38:52	0.08	55%
Transient 3	09:41:36	09:41:35	0.16	44%
Transient 4	09:41:43	09:41:42	0.08	34%
Transient 5	09:49:14	09:49:13	0.16	38%

The PQM located at the customer C33 also recorded five voltage transient events during the SMs switching. The customer C33 was located close to the substation and was not on the same feeder as of C32 and C34. The PQM at C33 recorded voltage transients when a SM on the same feeder was reconnected and was probably drawing high inrush current which resulted in voltage transient. Table 25 shows the time instants of voltage transients recorded in the PQM at C33.

Table 25: The time instants of transient events recorded in PQM3 during Test 3.

PQ event (Voltage transient)	**C33 (Associated SM was always ON) Moment of Transient recorded**	**Duration of the transient (millisecond)**	**Percentage of voltage change from the nominal value**
Transient 1	09:43:47	0.08	31%
Transient 2	09:45:03	0.16	43%
Transient 3	09:45:18	0.16	55%
Transient 4	09:45:34	0.16	35%
Transient 5	09:48:38	0.16	54%

As seen from Table 24 and Table 25, four voltage transients would have recorded in the PQMs during the Test 3 if the +/- 50% transient limit was used as it is practiced for voltage transient measurement. The Tables also show that the duration of the voltage transients were between 0.08 ms to 0.23 ms. Since, the duration of the transients are very short, the voltage transients may not impact the performance of the home appliances significantly.

Figure 17 shows a voltage transient event recorded in the PQMs at C32 and C34 almost at the same time. The loads of the associated customers were operating in normal mode before the transient event was recorded. The Figure shows the phase currents of the C32 and C34 respectively and presents the impact of the voltage transient on the load current of the two customers. The current distortions at C32 and C34 are not seen at exactly same instants in the Figure which could be because of time delay between the PQMs. As seen here, the voltage transient created little impact on the load current of the two customers. The phase currents were distorted due to the presence of transient on the voltage waveform. According to [59], the transient events with durations of fractions of millisecond and deviations of less than 60% of the nominal value will not damage the sensitive loads of the customers.

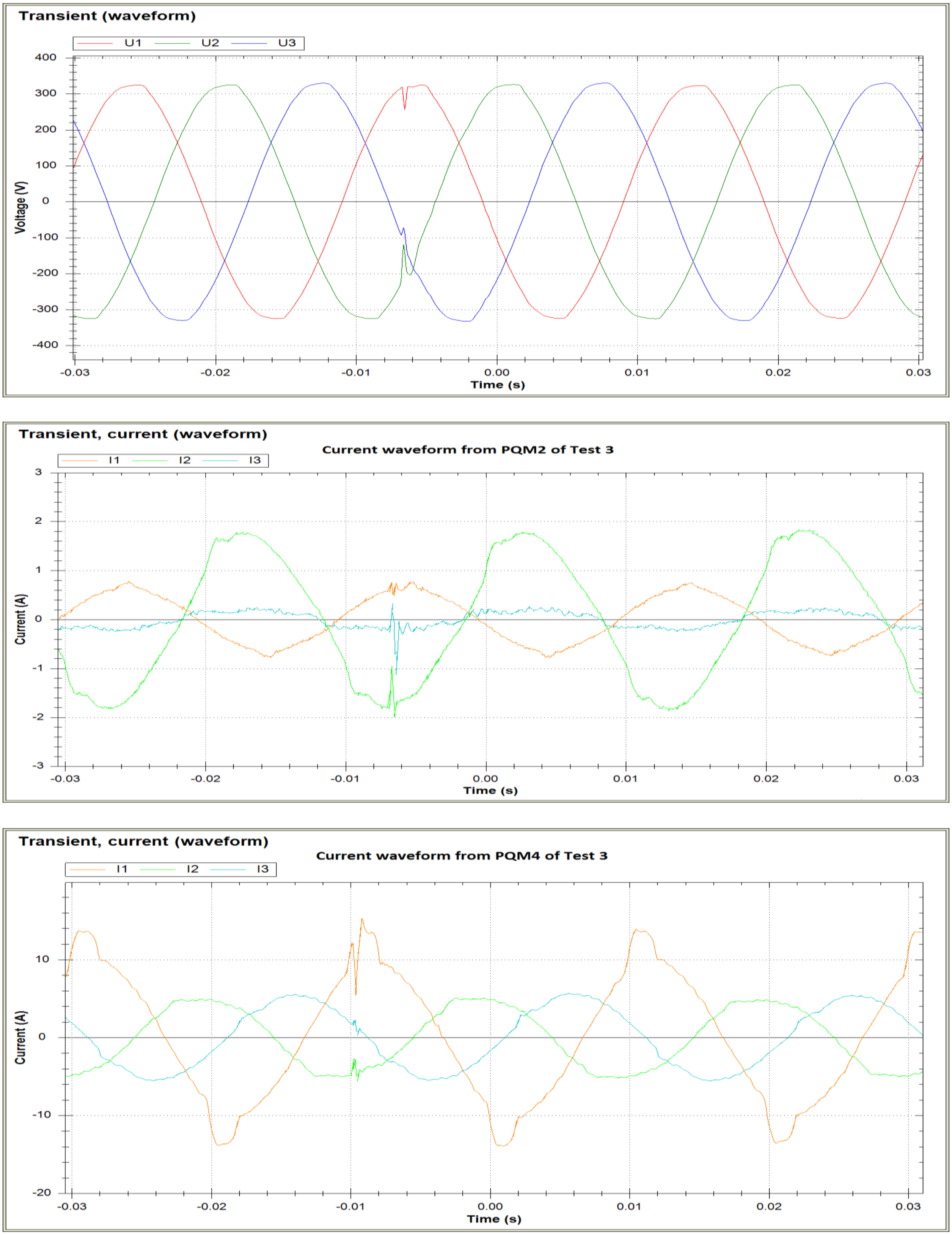


Figure 17: Currents and voltages of a voltage transient event recorded at customer C32 and C34 during the Test 3

Chapter 6 Closure

This chapter presents the main conclusions from this thesis work. Possible ideas for future work are also presented in this chapter.

6.1 Main conclusions

The thesis work focused on the impact of multiple SMs switching on the PQ of the grid and performed three field tests on multiple SMs switching with a main focus on PQ. Moreover, this thesis work investigated how the existing smart metering system performs with multiple SMs switching to find the limitations or prospects of implementing this switching technique for large scale of customers in emergency case. The main conclusions from the thesis work are listed below:

a) The test results show that the SMs switching did not create remarkable voltage variations e.g., flickering effect or THD (%) at the customer level and also at the substation level. Although, transient events were observed only at some customer level but not at the substation level. However, the transient events were recorded when +/-25% threshold limits used in the PQMs instead of typical +/-50% threshold limits. The transient events show that only four events out of twelve transient events exceeded the limit of +-50% but the values were below +/- 60 %. Moreover, the duration of the transients were very short e.g., 8 ms and 16 ms. The literature study on the impact of transients on the sensitive loads shows that the loads can withstand more higher voltage for very short duration. The reason for the transient events could be the inrush current of the loads when SMs were reconnected and it is expected to have such kind of transient events during reconnections.

b) From the PQ analysis of the field tests results it was realized that if the SMs switching technique is applied to all customers in a residential area which is connected to a LV substation, the loads of the customers could experience very small impact on PQ or no impact during the switching. Moreover, it was observed that if switching technique is applied by excluding the prioritized customers of an area, the PQ of the prioritized customers will probably not be impacted significantly during the SMs switching of other customers. Because, with the SMs switching, the load of the transformer is decreased or increased slowly compared to sudden change in the transformer load if customers are switched using the feeder fuse of the substation. More studies are however needed to fully investigate the impact of SMs switching for large scale of customers.

c) It was found that in some areas the voltage at the substation level could be as high as 240V during normal operation when the voltage is supposed to be around nominal value of 230V. If the SMs switching is applied to an area where the voltage is already high, then the excluded prioritized customers might experience voltage beyond the acceptable limit (244V) after the disconnection of significant load of that area. Similarly, the prioritized customers might experience LV across their load after the reconnection of significant loads if the voltage in that area is already very low. The voltages of the selected areas need to be checked before implementing the SMs switching technique for emergency grid management by excluding prioritized customers.

d) The performance of the existing smart metering system on multiple SMs switching shows that every MCU execute SM disconnection or reconnection one by one. In the investigated system, there are more than 50 MCUs with around 200 SMs per MCU and there are more than 500 MCUs with around 100 SMs per MCU. If the SMs switching is applied in areas where each MCU has around 200 SMs, the disconnection or reconnection process will take around 23 minutes if we consider 7 sec on an average for disconnecting or reconnecting SMs. But, there is one type of SM which requires two steps for reconnection of the SMs and based on the number of that type of SM in the selected area, the reconnection process might take even longer. It is also found that the MCUs can work in parallel if there are more than one MCU in the selected area. However, the SMs switching delay needs to be minimized to implement the technique for load management during emergency grid handling. The time required for SMs disconnection/reconnection needs be reduced either by minimizing the delay for SMs switching or by making the MCUs capable of executing multiple SMs switching at a time.

e) Moreover, some errors were found in the SM's real time switching status update report. The selected SMs reported real time switching status update to the CS. The report indicated failure of switching for some SMs while most of them were actually switched. The successes of failed indicated SMs were verified by checking the real time measurement of SMs one by one. But, the verification process takes long time and it is not possible to verify all the failure messages in case of large scale SMs switching. The reliability of the status update report needs to be improved, otherwise, this type of error might trigger unnecessary steps by the DSO e.g., sending people to replace or use optical eye for reconnecting the SMs. Finally, this type of misleading errors in the report might create economic impact on the DSO.

f) Furthermore, the investigation on the performance of the existing smart metering system indicated that the SMs reconnection process might take very long time compared to the planned time if the power supply to the customers is disconnected from the substation. The ZigBee communication network might break down and it may take long time than planned to build up the ZigBee communication network after reconnecting the substation. This thesis work studied the communication tree of the ZigBee network and found that few SMs communicate directly to the MCU and most of the SMs require multiple hops e.g. up to six hops to communicate with the MCU. The SMs which communicates directly to the MCU can be called as critical SMs because other SMs depend on the success of these critical SMs. The dependent SMs are capable of finding another way to communicate with the MCU since the Zigbee network is a self-healing meshed network. But, the process of finding a new way might require few minutes to hours and could create a long delay in the disconnection process which needs to be improved. Therefore, in case of emergency load-shedding, the power supply should not be turned off from substation level after disconnecting the SMs. The disconnected SMs would then retain power and keep the communication network alive and it would be easy to reconnect the SMs within the planned time.

6.2 Future work

The following ideas are few examples for continuation of this thesis, either as a complementary solution or in addition to the issues raised in this thesis.

- This thesis work performed several field tests on multiple SMs switching only for a small group of customers at a time and analyzed the impact of switch's operation on the PQ of the existing distribution grid. However, more research needs to be done to investigate the impact of multiple SMs switching for a large group of customers. The PQ measurement data from the small scale test could be used to create a model. The model can be used to disconnect and reconnect loads during the normal operation and investigate what happens if different parameters of the model e.g., short circuit impedance or short circuit ratio at the connection point is changed.

- The test results show that some transient events were recorded during reconnection of the SMs. However, future work needs to be done to investigate if the aggregated transient events during large scale SMs switching could impact the PQ of the grid.

- The test results also show that the reconnection process of the SMs of a particular area might take very long time if the ZigBee communication network of that particular area breaks down due to disconnecting power supply from the substation level. More work needs to be done in identifying different switching strategies to mitigate this problem in case of large scale emergency load shedding. Moreover, the time required to switch ON or OFF the individual SM in normal operation and also one by one switching technique of the MCUs can be seen as a limitation in implementing the SMs switching for large scale. More research needs to be done to find out the limit of allowable delay for SMs switching and also to investigate what demands need to put on switches of the future smart metering system.

- The switching functions that are used today in the current generation of the SMs could be expanded more to include e.g. partial disconnection of a customer. The partial disconnection can be used to prioritize at each customer to obtain the desired function e.g., for the grid management with minimum disturbance of the customer. Moreover, different options could be explored for DSOs benefit from the smart metering system e.g., DSM. Furthermore, Home Energy Management System (HEMS) is also one interesting option that could be explored.

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