TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

GAGANDEEP SINGH

DESIGN AND ENGINEERING FOR SMART SECONDARY SUBSTATION AUTOMATION PANEL

Master of Science thesis

Examiner: Prof. Sami Repo
Examiner and topic approved by the Faculty Council of the Faculty of Computing and Electrical Engineering on 6th May 2015

ABSTRACT

GAGANDEEP SINGH: Design and Engineering for Smart Secondary Substation Automation Panel
Tampere University of Technology
Master of Science Thesis, 98 pages, 6 Appendix pages
May 2015
Master's Degree Programme in Electrical Engineering
Major: Smart Grids
Examiner: Professor Sami Repo

Keywords: Smart Grid, Distribution Automation, Secondary Substation, Smart Node

This M.Sc. thesis presents a systematic approach to enhance automation at the electrical distribution level by introducing multiple retrofit approaches in existing secondary substations. This study has explored insights into providing intelligence to the secondary substation efficiently in terms of dimensions, cost and communication needs. The designing of a retrofit product has been accomplished taking into consideration the current network status, the present need and the future compatibility for Smart Grid. Although, the new device has been designed based on the Finnish network need, it is fully compatible with electrical networks worldwide.

Initially a comprehensive review of the theory and literature related to present network configuration, distribution automation, Smart Grids and all relevant areas was conducted. This was followed by a review of the reports of transmission and distribution networks operators in Finland and product brochures from various manufacturers in order to create a framework. This was complemented and further verified by the primary collection of data in the form of interviews and discussions with representatives from these companies. Based on all this information, the operation within the network was emulated and the final product was designed.

The product provides practical capabilities from the basic monitoring to the full automated control with decision making capabilities locally or remotely through the network control centre via SCADA. Being customizable and retrofit installation, its adaptability and scalability is based on the specific network need. Besides, as the product has been developed in the form a detailed research through collaboration with university researchers, product manufacturers as well as network operators, it is practically designed and is planned to be implemented soon. Although, there are other similar but less effective and less flexible products available, they lose advantage when it comes to compatibility. The research represents one of the first attempts to design a customizable product for the medium voltage level network automation and the retrofit approach with its modular and scalable feature provides originality to it.

PREFACE

The study has been conducted and written by the author as a thesis for M.Sc. Electrical Engineering with majors in Smart Grids at Tampere University of Technology (TUT), Finland and as a research project for VEO Oy, Finland. Due to its novel and intricate nature, the study brings together unique expertise to find solutions by combining the academic theoretical knowledge with practical application skills. The outcomes achieved by the research are a result of the support and collaboration of all the stakeholders without which this would have been just a few words on paper.

At TUT, I am grateful to: my thesis supervisor Sami Repo, Professor at the Department of Electrical Energy Engineering for his support, feedback, constructive criticism and understanding during the research process while overcoming geographical limitations to provide guidance; all academic and non-academic staff for their support towards getting all the official work done in a swift manner.

At VEO, I would like to render my special thanks to: Visa Yliluoma, Executive Vice President for believing in me and my potential to carry out this research within the tight schedule and for sharing experiences and providing invaluable information; Ralf Söderholm, Engineering Manager for the aspiring guidance, friendly advice, boosting my morale and confidence and for always being funny; Juha-Matti Hännikäinen, Senior Design Engineer for brainstorming ideas into concepts and being supportive; all the colleagues for always taking my queries about the research and about the Finnish culture with a smile; and everyone at VEO for their continuous and overwhelming support, encouragement and feedback throughout the process of research.

I would also like to acknowledge representatives from various organizations for the interviews who took out time from their busy schedules for the research. I am sincerely grateful to them for sharing their unbiased perspectives and illuminating views on a number of issues related to the research.

A warm and loving gratitude goes to my family especially my mother and my brother for always inspiring and encouraging me to be the best I can and finally this beautiful world which, as Paulo Coelho says, is always conspiring to help me achieve my ambitions.

All of you made it possible to accomplish this challenge.

Thanks a lot! Paljon kiitoksia! Tusen tack! Lakkh lakkh dhannwaad!

2015

Gagandeep Singh

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LIST OF ABBREVIATIONS

ADA	Advanced Distribution Automation
AFM	Automatic Fault Management
AGC	Automatic Generation Control
AI	Artificial Intelligence
AMR	Automatic Meter Reading
AR	Automatic Reclosing
ATS	Automated Transformer Substation
AVR	Automatic Voltage Regulators
BEMS	Building Energy Management System
BMS	Battery Management System
CA	Customer Automation
CAIDI	Customer Average Interruption Duration Index
CB	Circuit breakers
CICED	China International Conference on Electricity Distribution
CSS	Compact Secondary Substation
CT	Current Transformer
DA	Distribution Automation
DAR	Delayed Automatic Reclosing
DAS	Distribution Automation System
DER	Distributed Energy Resources
DMS	Distribution Management System
DR	Demand Response
DSE	Distribution State Estimation
DSM	Demand Side Management

DSO	Distribution Systems Operator
DT	Distribution Transformers
EMS	Energy Management System
ESS	Energy Storage Systems
EV	Electric Vehicles
FA	Feeder Automation
FACTS	Flexible AC Transmission Systems
FLISR	Fault Location, Isolation and Service Restoration
FM	Facilities Management
FTU	Feeder Terminal Unit
GIS	Geographical Information Systems
GOOSE	Generic Object Oriented Substation Events
HELEN	Helsingin Energia
HEMS	Home Energy Management System
HMI	Human Machine Interface
HSAR	High Speed Automatic Reclosing
HV	High-Voltage
ICT	Information and Communication Technology
IDA	Intelligent Distribution Automation
IED	Intelligent electronic devices
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISGT	Innovative Smart Grid Technologies
LFC	Load frequency control
LM	Load Management
LN	Logical Nodes

LOM	Loss of Mains
LTC	Load-Tap-Changer
LV	Low-Voltage
MAIFI	Momentary Average Interruption Frequency Index
MAS	Multiple Address
MDAS	Meter data acquisition system
MV	Medium-Voltage
NCC	Network Control Centre
NOP	Normally Open Point
OMS	Outage Management System
PLC	Power Line Communication
PMU	Phasor Measurement Units
PS	Primary Substation
PSS	Power System Stabilizers
RMU	Ring Mains Unit
RTU	Remote Terminal Unit
SA	Substation Automation
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCB	Shunt Circuit-Breaker
SD	Switch-Disconnector
SEM	Smart Energy Meters
SHG	Self-Healing Grid
SLD	Single Line Diagram
SN	Smart Nodes
SS	Secondary Substation

SSS	Smart Secondary Substation
STS	Smart Transformer Substation
T&D	Transmission and Distribution
TS	Transformer Substation
TSO	Transmission System Operator
TUT	Tampere University of Technology
VPN	Virtual Private Network
VT	Voltage Transformer
WBSEDCL	West Bengal State Electricity Development Corporation Limited
ZC	Zone Concept

1. INTRODUCTION

The world population with its economy is growing and so is the demand for electricity. Throughout the developing world, this growth in electricity comes along with the requirement to build new generation plants, transmission and distribution networks and the necessary systems to monitor and control them. Within the developed world, the pace of growth of this demand is not that rapid but there is another pertinent matter to be taken care of. As the necessary requirements have been fulfilled, the need has moved up, in accordance with Maslow's hierarchy of needs theory, to the next level which is reliability of supply. This reliability is entreated from the point of view of the network as well as the supply. Although the need for optimum level of reliability has always been there, this level is continuously changing. Now the requirements for supply reliability have increased from 'physiological' and 'safety' levels to 'social' level.

The systems at the generation side are reliable enough but the network reliability is an issue due to its vast spread as well as the geographical settings in which they are located. Going along with the saying 'To err is human', changes have been made to reduce the human interface as much as possible and the move towards automation has been dominating for a long time. The latest generation and transmission systems are fully automated and are currently unmanned with the control being taken into hand in case of non-cleared faults or for maintenance. Thus this need becomes the dominating driving force for increasing automation in all levels of distribution network as well. Apart from the improvement in reliability of the supply, this has the potential to bring in an improvement in the operational efficiency of the network company. As part of the efforts towards automation at the distribution level, the Smart Secondary Substations (SSS) at the distribution level have the prospect to provide a useful approach for planning and upgrading the distribution networks. This 'smart' concept is replicated throughout the electrical network under the notion of 'Smart Grid' (SG).

1.1 Research Problem and Motivation

With the increased deployment of Distributed Energy Resources (DER) into the grid, it becomes complex to manage the network operations but SG applications improve the capability of electricity producers and consumers. This drastically changes the way the system and the network switching is controlled and implemented in case of faults. It necessitates the usage of remote measuring, communication and control systems for the switching equipment (relays, breakers and others) in the distribution network. This control has to detect and rectify the faults in the least possible time in the distribution system; similar to how is implemented at the transmission level. The main switching elements (disconnectors and breakers) of the feeding line are present in the distribution level substation also known as the Compact Secondary Substations (CSS) and these in the current scenario are not well automated. One of the reasons is that the CSS manufacturers do not have research or technical capability to design new ‘smart’ products and it becomes complex for the network operators to modify these products and have to use them as they are.

This automation is necessary in the network has become the motivation of the thesis and thus the research intends to unravel this problem. Therefore, the product designed in this research would assist in improving the reliability of the network by reducing the outage time, thus creating savings for the distribution company. Apart from this main benefit, the system could also be customised based on the needs to integrate the customers with Distributed Generation (DG) (solar, wind and others) to the network while keeping the control and ability with the network service providers to closely monitor, shift, and balance the load in a way that allows to reduce peak load leading to the creation of smart grids. Thus, network service providers are also benefitted as they have controllability over the new DG in the system which can be designed for island operation, thus increasing network reliability even further. With the basic idea of what this research is about, it is prudent to understand the context and the environment in which it functions which is briefed in the upcoming segments.

1.2 Overview of Electrical Network

The rudimentary structure of the electrical power system has three key elements: a source, a transportation medium and a sink. The source and the sink are the energy producers and consumers respectively but the transportation medium is the entity that connects them through a network. This network in the modern day is split into two main tiers:

1. Transmission network (High-Voltage (HV) and Extra-high Voltage (EHV) network at the order of hundreds of kVs)
2. Distribution network
    a) Primary distribution network (Medium-Voltage (MV) network at the order of tens of kVs)
    b) Secondary distribution network (Low-Voltage (LV) network at the order less than 1kV)

Together, the entire network is referred to as the Transmission and Distribution (T&D) system [1]. As apparent in the classification above, the elementary network segmentation is based on the voltage levels and these levels vary throughout the world along with the frequency (50 or 60 Hz). The use of transformers (within or outside the substation) facilitates operation of different segments of the system at different voltages while specifying the boundary between transmission and distribution systems [1]. As the research has implication in the Finnish scenario, it becomes necessary to understand the Finnish network which is done in the next section.

1.3 Synopsis of Finnish Electrical Network

The power system in Finland is part of the inter-Nordic power system composed of the systems of Sweden, Norway and Eastern Denmark which is in turn connected to the system in Continental Europe by means of High Voltage Direct Current (HVDC) transmission links. In addition, there are HVDC transmission links to Finland from Russia and Estonia. The Finnish electrical network is thus relatively well developed and a brief description is provided in the following subdivisions:

1.3.1 Network Configuration in Finland

Based on the distance parameter, the Finnish electricity network can be segmented into three parts [2]:

1. <u>Main grid</u> : long distance overhead transmission connections (14,000 kilometres in total) and high transmission voltages and operate between 110 and 400 kilovolts
2. <u>Regional networks</u> : overhead operate at 110 kilovolts (difference between the regional and the distribution network is based on the voltage level) (can be 45kV as well in some cases)
3. <u>Distribution networks</u> : use the main grid through the regional network or connect directly to the main grid and operate at 20, 10, 1 or 0.4 kilovolts

Based on the voltage levels, the Finnish electrical network can again be segmented into three parts [2]:

1. <u>High Voltage</u> : between 110–400 kV (approx. 20,700 kms of network length)
2. <u>Medium Voltage</u> : between 1–70 kV (approx. 137,000 kms of network length)
3. <u>Low Voltage</u> : up to 1 kV (approx. 232,400 kms of network length)

1.3.2 Automation Level in Finland

One of the potentially rewarding developments for power systems has been the increasing use of automation techniques for monitoring and control. The automation areas include: Substation Automation (SA), Network Automation and the Customer Automation (CA). The controllability at the generation plants and transmission lines have already been applied with a strong automatic mechanism using Power System Stabilizers (PSS), Automatic Voltage Regulators (AVR), load frequency control (LFC), Automatic Generation Control (AGC), and Flexible AC Transmission Systems (FACTS) devices [3]. This leaves out the distribution network which is somewhat haphazardly automated due to the presence of old as well as new equipment within the network. The following points brief about the automation level existing in the Finnish grid:

1. Transmission Network Automation

The transmission network i.e. HV network covers entire Finland and is under the monopoly of Fingrid, a Finnish Transmission System Operator (TSO). The use of automation has risen sharply in the electrical and power companies and one of the most significant grid automation steps was taken in the 1970s when Supervisory Control and Data Acquisition (SCADA) was introduced and it has become an irreplaceable part of the transmission network since. Recently, with the development of microprocessor and computing technology, the remote control systems have also evolved and have become widely adopted along with the Energy Management System (EMS) and the Network Information System (NIS) linked to SCADA.

2. Primary Substation Automation

SA, specifically for the Primary Substation (PS) which is a HV/MV substation in Finland, has traditionally been a combination of remote and local control with monitoring and protection capability. Different kinds of automation solutions are used at different levels: substation transformers, Circuit Breakers (CB), isolators, relays, instrument transformers and auxiliary systems for control and supervision. The features of relay protection of feeders with Automatic Reclosing (AR) and the transformer voltage control are used in all substations throughout Finland as part of SA. The automation functions (alarms and monitoring features) that were previously carried out by independently functioning devices have now been integrated (either partially or fully) via local microprocessor-based automation system to the Network Control Centre (NCC) via SCADA system with additional DMS, Automated Mapping (AM), Facilities Management (FM), Geographical Information Systems (GIS), Distribution Management System (DMS), power quality monitoring and other systems. The latest development trend has been to move from a centralized to a decentralized system where the necessary decisions are taken locally and the control is handed over to the NCC only in case of need, thus reducing the information transmission congestion.

The automation of this PS can also be considered a part of the distribution network automation and as the research focuses more on the distribution level, it is elaborated in the next point.

3. Distribution Network Automation

The distribution network comprised of the MV as well as the LV network is the most widespread network for electricity supply and is discussed here:

i. Primary distribution network (MV network)

The distribution at the MV level is done through the Secondary Substations (SS) also known as the distribution substations. In Finland, the SS are implemented in three configurations [2]:

1. Located on poles (primarily in rural areas)
2. Located in the basements of apartment blocks
3. Located in substation buildings in parks (SS)

This also includes the feeder automation which has remotely controllable disconnectors (common in overhead MV network) as well as reclosers along MV feeder (time grading with circuit breaker / protection relay at PS in some cases.

ii. Secondary distribution network (LV network)

The LV network is the connect point for the end users or the customers. The automation for energy meters is in terms are the so-called Smart Energy Meters (SEM) which form an integral part of the SG concept, Finland has been in the forefront in deploying SEM at the customer level and all the residential loads were equipped with SEMs by the end of 2013. The networks are supplemented with a data network with two-way communication for energy monitoring. Additionally, there are plans for future for using this two-way communications to manage DG (home PV or small wind) as the energy will flow in both directions in that case and the data transfer (and power flow) would take place from the network company to the customer and vice versa. This information sharing also enables network management when the operating methods of the network reconfiguration are needed to be applied. The various features that have been implemented so far are as follows:

- Remote (automatic) meter reading for billing purposes
- Information collection on customer load profiles and network losses for future network planning
- Automatic fault location in LV networks and outage communication
- remote disconnection of customer
- remote control of specific load (typically heating)
- some indicative information about power quality
- remote changes for tariffs

The automation for load control is for the DR (out of its multiple other applications) and its purpose is to limit the peak load. Currently, the controllable elements of the network are predominantly the electric heating loads and the control for this enables the load to be switched off by the network operator when needed (if the DSO and the customer have agreed and signed a contract), but this topic is still under constant debate due to the rights of use and other issues although the contracts to specify these already exist. The CA also comes under this category and includes the automation for the energy meters, load control, home and building automation and more specifically Home Energy Management System (HEMS) or Building Energy Management System (BEMS) and other aspects.

As the overall penetration of automation technologies at the distribution level in Finland still has more scope to develop, the network need and its compatibility with the latest smart grid level is discussed in the next section.

1.3.3 Integration with the Smart Grid concept

SG can be understood as the ‘Internet of Things’ for the electrical grid and in Finland this has come into existence due to the development and increase in use of ICT. The electrical network in Finland is already fairly intelligent and can be understood as having Smart Grid 1.0 already in use [2]. The features of this intelligent use of the grid include but are not limited to automatic fault locating and separation, optimisation of network use, and remotely read meters. The level of SG 1.0 has been reached with the implementation of the SEMs and the capability of two-way data transfer between the customer interface and the network. There is a need for the utility companies to analyse the network sensitivity towards end users for upgrading existing as well as install new MV distribution networks for integrating into SG [4] and this need is desired in Finland as well. As the HV and LV level by now have the sufficient level of smart technologies as already explained in the segment before, the focus here is on the MV level as illustrated in the next part.

1.3.4 Network need for integration

SG concept is manifested at all levels of electrical network but one of the levels where the need is the most and benefits can be of greatest value is potentially within the MV level of distribution network. SG necessitates a reliable electrical distribution system which enables the customers to participate in the electricity market via the usage of two-way flow of energy and information. The two-way information flow is already present but the two-way flow of energy is coming soon as well with the perspective of the Finnish government and the EU going towards the RES. As these RES, as part of the DG, would be put on the distribution network, this puts strong requirements on the MV network and its operation as the SG functionality has not been implemented to the necessitated extent yet although it is needed in the future. These requirements arise due to the complex flow of energy due to the presence of RES which are intermittent. As this does not form the key issue of this research, it is not discussed further.

The MV distribution network comprises of different components from manufacturers and as a result the control and monitoring of faults and operating conditions on the distribution network are un-advanced compared to the ones at the HV levels. An example of this is the Fault Location, Isolation and Service Restoration (FLISR) process, when the recloser on the overhead network has failed to rectify the fault, the process is primarily based on reports from customers and manual supervision. For the outgoing MV feeders from the PS, a lot of information related to fault location is received by analysing fault recordings from protection Intelligent Electronic Devices (IED), referred to as relays in the past, which us utilised by SCADA for estimation of fault distance and by GIS for fault location. The process of FLISR including switching actions may be automated assisted by the DMS for proposing the best switching sequence for CBs and remote/manually controlled disconnectors. In Finland, the distribution at the MV level is done using SS as explained before and the CSS known as the ‘Puistomuuntamo’ in Finland, translated roughly to as the Park-Substation, are gaining ground with their commissioning being the easiest of all the available options and this being one of the key components of reaching the SG implementation.

Figure 1-1: Puistomuuntamo [5]

The basic SS consists of the transformer, MV switchgear and LV switchgear. The MV switchgear predominantly consists of a Switch-Disconnector (SD) (with or without a fuse) also known as the load-disconnector with little or no automation capabilities. The SD has the capability to switch load currents (normal disconnector cannot do this without significant risk, tear and wear) and can thus be utilized for relocating the open switch predominantly for supply restoration purposes. If the location of the open switch in the radial network is changed during normal operation, the ring has to be closed first by closing the SD at open point and the one at the new open point can be opened to maintain supply continuation. The reclosers are already present on a few of the overhead MV feeders where the feeder starts as a cable and continues as an overhead line. The usual capability is for the manual switch-off of a specified amount of load current and reclosing for up to 12.5 kA of short-circuit current. Examples of SDs with/without fuse are shown in Figure 1-2 and Figure 1-3 below:

Figure 1-2: Switch-Disconnector with fuse

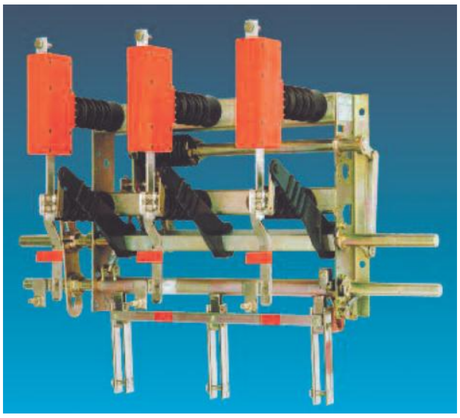

Figure 1-3: Switch-Disconnector without fuse

The SD can be manually operated (as in the current situation) or operated via a motor operation using a motor actuator. The presence of the motor operation is the basic need to implement any kind of remote capability to operate the SD. The minimum requirement for implementing automation capability is the remote monitoring of the SD status which is implemented in Finland but only in a few applications. Currently, the communication for this is carried out mainly on 85 MHz frequency band of the radio network which is outdated and other communication options are discussed later in the thesis. The monitoring including the fault indication as part of the network automation can speed up the fault troubleshooting process and further advanced benefits can be attained from the next step of remote control in addition to the formerly discussed monitoring. A few of the requirements for the automation of PM include:

1. Remote control of the SD or breaker

    - Provision for motor actuator/controller
    - Addition of control unit (with local and remote operation capabilities)

2. Monitoring and Measuring Capabilities

    - Voltages (3-phase) using Voltage Transformers (VT)
    - Currents (3-phase) using Current Transformers (CT)
    - Temperature sensor
    - Active power, power factor and others
    - Reactive power consumption (new requirement to be applied from 2016 in Finland)
    - Total Harmonic Distortion (THD)
    - Voltage fluctuations
    - Frequency fluctuations
    - Others

3. Protection Capabilities (similar to MV feeder protection plus more)

    - Overcurrent protection
    - Distance or differential protection
    - Earth fault protection
    - Surge protection
    - Transformer protection
    - Many others, mentioned later in the design stage

4. Communication Capabilities

    - Wired or wireless
    - Remote Terminal Unit (RTU) if needed
    - Antenna on roof for reliable signal reception

5. Auxiliary supplies with back up energy storage using batteries for:

    - Relay operation in case of loss of main supply
    - Motor operation of SD or breaker
    - Space heater
    - Automation devices in general
    - Other transducers

6. Reliability Enhancement:

- Remote FLISR from SCADA/DMS
- Decentralized FLISR (peer-to-peer communication between IEDs)

All of these requirements have been analysed later in the analysis and discussion chapter-4 and used for designing the final product. The remote control function of the SD is the most essential requirement of the distribution network automation as the FLISR process can be executed quickly, whereby outage interruption duration is shortened and the harm is reduced. The remote control operation of the SD along with other automation capabilities of the PM can bring out enhanced results in terms of the improved reliability in locations where the interruption costs can be reduced the most. The places are generally the network points which are located far from the control room (e.g. rural areas), are situated in the locations having significant impact, have higher fault rates or

This is discussed in detail in the theoretical background chapter 3.

1.4 Thesis statement

‘‘Utilization of existing equipment; compatible relays, switch-disconnectors, reclosers, breakers and others, to design new customized product for advanced distribution automation at the ‘Secondary Substation level’’

1.5 Scope

The scope of the thesis consists of the following two parameters:

1.5.1 Research

As the study is about the design of a novel product, it needs to first analyse the need of the market. This is accomplished by analysing the literature coupled with first-hand information from the distribution network companies as well as from the PM manufacturing companies. As there is still a gap between the theoretical designed systems and practically implemented system, the study also aims to narrow that gap and for this the analysis for the existing products is also included. This is supplemented by the primary information using interview with DSO’s (VSV and others) and the product (SS, IED, and others) manufacturers. The need for the customizable solution and how to realize it is also within the scope.

1.5.2 Implementation

The implications of the researched information about the current scenario and the need are implemented through the creation of a customizable design for the product, i.e. Smart Distribution Automation product for SS. The scope for this comprises of:

1. Dimensioning: Components sizing (relays, breakers, battery and others)
2. Pre-Engineering, Designing and Engineering: Connection of components with existing or new system
3. Compatibility analysis: Need based selection of the components for customizable solution and their inter-operability check
4. Grid connection: Connection to MV 20kV system (or LV 0.4kV system)
5. Communication prospects:
    a. Power Line Communication (PLC)
    b. Fibre Optic (better option but probably not possible due to large distances)
    c. Ethernet
    d. Radio
    e. 4G
    f. 3G
6. Follow standards: IEC 61850 and others for protocol compatibility

1.6 Aim

This aim of the research is to propose and research practical methods for linking/integrating the existing equipment and design a customizable product or solution which can be used for purpose of automation at the Secondary Substation level to allow remote monitoring and control of distribution network.

1.7 Objectives

The aim of the research is fragmented into objectives which are as follows:

- To study the various components (switching, automation, control communication and other components) and analyse how they can be used utilized for switching on or off a part of the distribution network (in case of faults)
- To study and obtain information about the existing products and components presently available in the market
- To study the products (communication units, information exchange protocols, and possible gateways) and analyse how they can be used utilized for communicating the signals from the transformer substation to the control centre (with distribution level SCADA)
- To create a preliminary specification needed for designing and integrating them in a compatible way (based on calculated assumptions)
- To design a customizable product that can be installed at the PM to monitor and control the equipment present there

2. RESEARCH METHODOLOGY AND MATERIALS

This chapter illustrates the framework around which the structure of the research is based. This is described in terms of the research design and the process followed for it.

2.1 Research Design

The study, due to its novel character, has made use of the qualitative approach and explored the literature published up to date with the analysis of its practical application aspects in present distribution network. The research has been conducted by collecting the required data according to the research needs by using the literature sources such as books, articles and journals but to complement the research, primary source in the form of interviews and discussions was also utilized.

The initial focus of the research was desk-based study which was conducted first and then followed by interviews and discussions as part of primary research which was used to examine and verify the validity of the findings to eventually provide a platform for discussion and developing the product. The aim and objectives of the research were identified to define a path for the study and to keep track of progress as explained in the Introduction Chapter-1. The two phases of secondary and primary research were segmented into six steps in order to fulfil the objectives of the thesis:

- Firstly, a broad literature review was conducted by examining and using a number of secondary sources in the form of various information sources containing data that have already been collected and compiled consisting of readily available compendia and reports to gather data and current theories for the initial study. This included numerous books and latest articles from sources including but not limited to IEEE and others.
- Secondly, to complement the findings from the literature review, interviews and discussion sessions with representatives from diverse organizations were conducted to analyse the current need and the solutions already available. The information gained from the broad literature review was utilized to follow and conduct interview and discussion sessions and thus it was based on the findings from the desk-based study, which utilized reports and other sources as mentioned in the first point, to make it thorough and comprehensive. These findings formed the basis for creating different interview templates and discussion topics which were then conducted, which were rendered sufficient to complement the secondary research. This specifically included in the interviews about what the needs of the present network were and what and how they were being met by the different product manufacturers.

- Thirdly, preliminary discussion and analysis with detailed distribution automation methodologies and processes was conducted to identify and examine the effectiveness of the proposed approach and its suitability to the existing distribution systems.
- Fourthly, analysis using information from practical existing equipment was be accomplished for the purpose of verifying the results of the research. This made the research thorough and comprehensive with the practical aspect to it.
- Fifthly, to verify the findings from the primary and secondary sources, basic analysis of the automation system functionality using simulation in software was performed followed by its emulation within the network.
- Lastly, a detailed discussion, analysis and conclusion was followed based on the information assessed in the literature review and the analysis to explore the means of improving the automation level in the distribution network using SS as the medium.. This, complemented with the feedback and suggestions from the interviews and discussion sessions, was utilized as a rigorous foundation to base the conclusions on and in delivering the final outcome, conclusions and suggestions for future studies and well as the design for the new product.

2.2 Research Process

The qualitative data collection for the research followed a continuous process. As previously described, the first phase included the literature review based on the numerous books, articles and journals on the various issues on automation for the distribution network. This was followed by analysing the reports and publications of organizations for extended literature review and to explore their need. With the realizations of the distribution network need at hand, the formulation of research questions and their categorisations into segments, as mentioned in the introduction, was prepared. This resulted in a preliminary framework with findings for the study from the secondary sources which was enough to base the conclusions on. But to make it more practical oriented for application in practice and to offer pertinent real-world recommendations, its verification in the project context through appropriate method of primary data research was necessary.

The primary data collection could have been executed in several ways. The various applicable options available were the observation method, case study, discussion sessions, questionnaires and interviews. The observation method was phased out as inappropriate as it takes enormous time along with the subjectivity that it introduces about the interpretation of observation [6-8]. A case study also requires long time which was constrained in this situation. The results obtained in a case study are from only one organization in which it is conducted and are biased towards it [8]. Moreover, this method is based on several assumptions which may not be realistic in all situations [7]. Therefore the possibility of a case study was ruled out. Although the case studies, as already compiled reports, were fully utilized. Another option was using a questionnaire as it is a standardised means of gathering data, there is no possibility for explanation in case of confusion in the questions which the participants might misinterpret [9], this was accompanied by interviews. Moreover, the questionnaires are incontrollable, slow to receive information from, have ambiguity in replies or even their omission [7], thus the need for interviews alongside them was necessary.

Finally, interviews and discussion sessions were chosen as the method for collection of primary data as more information in greater depth can be obtained [6, 8]. Interviews and discussion sessions can probe into exploratory questions depending on the context with the benefit to ask follow up questions which are missed if a mail survey using questionnaire was used. Interviews and discussion sessions avoid misinterpretations by adapting the language accordingly to the ability or educational level of the person interviewed [7, 8]. Moreover, they incorporates the observation method which can be applied to the verbal answers to numerous questions [7] . To embrace this and obtain current in-depth understanding, semi-structured and open ended interviews and discussion sessions were concluded to be the optimum option. This ensured that the same information was collected but it still allowed for a certain amount of freedom to adapt to the context and to fit to the situation of the interviewee. It makes it easier to obtain personal information (tacit in some cases) which is hard to obtain through questionnaires or other medium [7, 9] and resistance to answering some questions can be overcome with appropriate usage of interviewer’s skills [6, 8].

The approach considered face-to-face interviews but due to diverse geographical locations of the interviewed personnel some of the interviews were conducted via telephone which still maintains the personal contact between the respondent and the interviewer. The discussion sessions were all conducted in person. For better handling of the questions as well as the situation, the interviews and discussion sessions were conducted by the author himself while avoiding any bias that could possibly influence results. This facilitated as the author had the understanding of the importance as well as background of the study. The next step was of conducting the interviews and discussion sessions as a data-gathering method of the qualitative research. This was followed by the emphasis on the methods of description, analysis, and interpretation of the interview and discussion session data as part of the process.

3. THEORETICAL BACKGROUND

This chapter provides a review of the literature relevant to the topic and creates a problem-setting based on the issues raised in the theory. This follows from the introduction chapter and describes the theory related to it.

3.1 Smart Grid

There is a need to enable the electric utility systems for operating the power system more effectively and efficiently for enhancing reliability, efficiency, power quality and utilization of distribution assets. On the other hand, there is also a necessity to provide information for enabling the customer to make informed decisions about energy consumption patterns and behaviour. SG can be defined as a power system which utilizes the latest technological advancements for accomplishing these two major goals [10]. The European Commission has also chosen SG as a key investment area for the future and the automation solutions are in line with this theme and assist in enhancing the responsiveness of the electrical network. As the electrical network is foreseeing major changes towards modernizations, the discussion on SG is presented in sections which are as follows:

3.1.1 Conception of Smart Grid

With the advancement in Information and Communication Technology (ICT) and the development of the latest sensor technology, the field of automation have reached new levels and within the power utility sector this has led to new products and solutions which are generally classified under the category of SG technology. The concept of SG has gradually become significant in the last few years as the technological solutions to realize it are available with the support of automation technologies for its implementation [11]. SG refers to a power system which possesses enhanced operational monitoring, control, intelligence, and connectivity via the utilization of advanced communication, electronic control and information technology [12]. Thus the concept of automation is extended to every level of the system including the metering, monitoring, protection, and control, leading to the formation of a smart distribution system.

From the generation point of view, SG supports small-scale, local and DG such as wind power, solar power and others, thus turning the consumer into a micro producer, often referred to as the ‘Prosumer’. This is necessary as the change towards the increase use of Renewable Energy Sources (RES), which have a difficult-to-predict generation pattern, is inevitable.

From the consumption point of view, SG provides the provision for flexibility in demand thus supporting the Demand Response (DR) feature which is a part of the Demand Side Management (DSM). This introduces more adaptability of the demand with the generation and the consumers can benefit, financially, from it as well while contributing towards the improved and efficient use of production resources and reduction in price fluctuations [2]. Electric Vehicles (EV) plug-in or hybrid, receive huge attention in the SG concept as their use increases, the potential of DR will enhance as these can potentially be used as controlled energy reserves when needed and thus reducing the need for Energy Storage Systems (ESS) in the network [2].

From the network point of view, SG is essentially a concept of a fully automated power network which provides the utility companies with full monitoring in real time and control over their assets and services using two-way flow of information between network nodes [13]. It is often referred to as functionality for remote monitoring and supervision of essential parts of the network via sensors and remote control of switches and breakers using functionality for communication. These solutions have been implemented on the network for a long time typically on the HV level transmission networks and in generation plants but the MV level distribution network which is more widespread has been left out. This functionality has also been introduced in the LV level distribution network lately through the implementation of the various smart metering systems. The Finnish Energy Industries summaries this essence and describes SG as a 'tuned' electricity network [2].

Although, the scope of definition for the concept of SG is extensive and varies across countries and companies, the essence remains the same which is to take the present day electrical systems to the next level. In line with this, the Smart meters implemented in Finland and the PV penetration in Germany, are few examples that show that some changes may take place at a faster pace. With due course of time, the understanding of this concept will evolve with the sharing of the visions for it and a common context will be reached. The change towards SG is more of an evolution than a revolution [2].

3.1.2 Technological perspective

IEEE defines SG as the next-generation electrical power system that is typified by the increased use of ICT at all the levels: generation, delivery and consumption of electrical energy [14]. Mohagheghi et al. describe SG in a similar manner from technological viewpoint as a power system that incorporates the state of the art in ICT in order to achieve enhanced operational monitoring, control, intelligence and connectivity [15]. These are very generic definitions of SG and focus on the blend of ICT for the whole electrical energy process. However, there is still a missing point that only a few have noted: the human aspect of SG. The people are the ones that design the system which runs these processes and the designing of these is the most essential and the most complex part. The complexity is partly due to the unavailability of technologies for all the processes and partly because of the presence of prevailing system which is very old and it's full up gradation in not feasible. Thus, SG encompasses a variety of tools, techniques and technologies that will allow energy suppliers to more accurately measure electricity flows and remotely control each point of the transmission and distribution network using two-way digital technology [16]. These tools and techniques, in addition to the technology, fulfil the additional requirements of SG.

3.1.3 Key features

The major facets of the smart grid concept include [10]:

- Smart Generation: new tools for using centralized generation facilities in the most efficient and economic manner and incorporating the upcoming DG and DERs
- Smart Transmission: Phasor Measurement Units (PMUs) and FACTS devices for much more effective and precise control of the bulk power grid
- Smart Distribution Feeders: new sensors that greatly improve visibility of conditions out on the electric distribution feeders (outside the substation boundary) and optimal control of distribution assets
- Smart Primary and Secondary Substations: which include expanded use of IEDs for optimal monitoring and control of primary and secondary equipment located inside the substation fence
- Smart Metering: advanced metering infrastructure that provide energy consumption information and energy pricing signals to the customer, supports demand response functions, and enables more efficient control of electric appliances as part of LV or home automation

In addition to these five facets, there is also a concept of Smart Market which is one of the latest topics under development. All of these individual smart aspects have to be connected via the utilization of the tools and techniques as explained before.

3.1.4 Smart Grid capabilities

The aspects mentioned in the last segment portray only one perspective of the SG and these vary from one person to the other. Although there has been much debate on the topic within the industry and among the researchers, a unanimous definition of SG and the capabilities it has and the areas it covers, is yet to be defined. Thus, advancing from the concept of SG, the emphasis could be shifted towards the smart use of the grid [2]. But nonetheless, the effects that SG will have on the electrical system are unanimously agreed to and the characteristics it may add to the grid include but are not limited to:

- Advanced monitoring systems to enable fast and accurate interpretation of the data
- Communication and metering infrastructure to access to the real-time information about the network equipment and resources

- Provision for an interoperable infrastructure for compatibility between products from different manufacturers
- Self-healing mechanisms for appropriate response to grid disturbances
- Provision for continuous addition of new DG
- Efficient DR programs for active customers participate
- Future proof design for flexibility and adaptability for accommodation of latest emerging technologies

3.1.5 Smart Grid for Distribution Network

As the topic of the thesis falls within the distribution network, the perspective of SG from this viewpoint becomes pertinent. Garcia et al. are of the belief that the fundamental components of distribution networks will be automated with SG which will allow a state diagnosis of the network leading to an enhanced management of the grid and an efficient integration of new DERs in addition to improvement in quality of service [17]. This automation aspect is very true and is the most essential. Mamo et al. also support this view and consider that with the growth of contextual and technical evolutions within the SG development strategy, the expectation from the automation of distribution network rises to provide innovative functions to the operators for enhanced network management [18].

With the stringent requirement for environmental conditions for the power plants and the availability of small renewable generation systems, the DER are increasing in the distribution network and with this comes the complexity to be handled in case of faults and to handle the intermittent nature of the RES. The target of SG can be achieved through the integration of intelligent micro grids which are small interconnected networks of DER systems (loads and resources) which can function in an on or off grid mode [13]. This leads to the island operation mode of the distribution network which is an essential function of the SG concept but its implementation is so far quite complex. Another feature of the SG as part of the distribution network is that it possesses a 'self-healing' ability which is to detect the fault, diagnose and determine the fault location, implement corrective action and restore supply of non-faulted section with little or no human intervention [19]. This leads to the fully automated operation mode of the distribution network which is again an essential but complex function of the SG concept. These functions come under the concept of automation for the distribution network within SG which is described in brief in the next segment.

3.1.6 Role of Secondary Substation and Automation in Smart Grid

The Secondary Substation (SS) is a key component of the SG concept. The basic terminology used is the SS with some authors referring it to as SSS or Transformer Substation (TS) or Smart Transformer Substation (STS) or Automated Transformer Substation (ATS). The term SSS refers to SS that provides different functionalities of monitoring, protections, autonomous decision making, remote control and others alongside the foremost objective of voltage transformation [11]. In Finland, this is predominantly pole-based with the latest trend being the Compact Secondary Substation (CSS) available as predesigned prefabricated product.

The concept of SG is based on wide spread information sensing from devices distributed on power network and utilization of communications solutions to meet operational requirements for the supervision and control functions [20]. Thus, the SS plays the role of a smart transducer node for collection and sharing of measured data from field devices (SEMs, ESSs, DERs and others) by using smart innovative devices. It further performs local automation functions with the ability to communicate with the NCC for the remote control and management of the network. Therefore, within the context of distribution network for the SG, the SS forms a vital building block of the distribution SG and necessitates an innovative progressive role [21]. This progression is in terms of its function as an integrating node where other information collecting field devices can be assimilated and some local automation functions can be performed with the ability to communicate with the grid NCC for the remote control in case of need. This needs the development of customized solutions based on new standardized components and product modules which can be installed compatibly with the existing infrastructure of primary and secondary substations [21] and this research attempts to fulfil this necessity.

Hence, SS for SG, through its services carries the potential to obtain and share enormous but relevant information about the operational state of the distribution network which further permits superior control of the network in terms of faster FLISR process, easy integration of DERs and EVs into the network and several others. For understanding the automation for the distribution network and how it can be carried out for integration to the SG, it becomes necessary to understand the basics about how it is configured, which is described in the next segment.

3.2 Distribution Network configuration

A three phase circuit coming out of the substation is known as a feeder [22] and there are numerous ways in which these feeders may be configured in a distribution network. Predominantly, distribution networks, both primary (MV) and secondary (LV) are designed as radial networks as they provide many advantages including [22]:

- Easier fault current protection
- Lower fault currents over most of the circuit
- Easier voltage control
- Easier prediction and control of power flows
- Lower cost

On the other hand, the loop networks are provided with normally open tie points for reliability improvement which renders the network ring formation capabilities. This comes under the concept of Ring Mains Unit (RMU) and shown in *Figure 3-1* below:

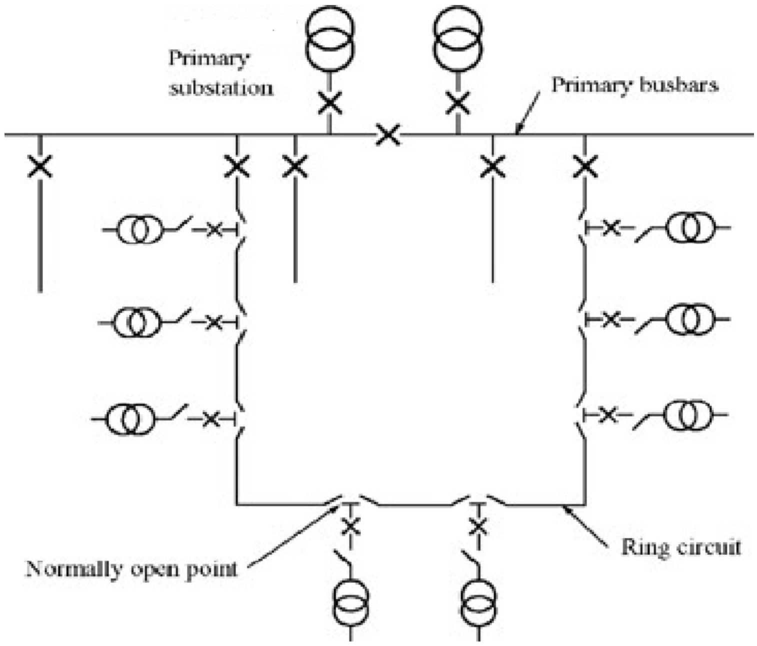

Figure 3-1: MV network in ring mains configuration

This requires the RMU unit as the basic component as shown in *Figure 3-2* below:

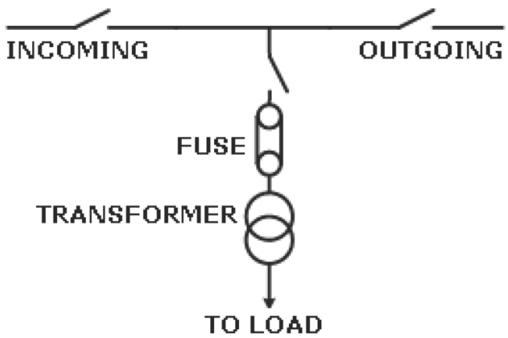

Figure 3-2: Basic RMU unit for SS

Thus in turn, the distribution networks are planned and built as mesh networks but operated as radial networks due to simpler switching and protection equipment in radial configuration but at the cost of reduced reliability [23]. The network is operated radially, but in case of fault on one of the feeders, the tie switch closes and allows a segment of the faulted feeder to be restored swiftly. The tie switch could be operated manually or remotely or automated switches or reclosers could be used for automatic operations. The implementation of this is discussed further in the analysis and discussion chapter-4.

3.3 Distribution Automation

With the increase in electrical power demand, the corresponding increase in network complexities necessitates enhanced levels of automation and communication for remote control as well as for management of power network [24], thus requiring the upgrading of the existing network infrastructure which comes along with numerous complicated changes. Along this need to improve the distribution system operating performance and to promote the application of ICT, The concept for the automation of the distribution network, within the scope of SG has been referred to with several but yet similar names. The basic terminology used is the Distribution Automation (DA) with some authors referring it to as Advanced Distribution Automation (ADA). DA emerged as a concept in the 1970s. As a vital element of SG, DA facilitates the utilization of the advanced computer and communication technology and infrastructure to develop the management and operation of distribution network from a semi-automated approach towards a fully automated one [12]. In the initial stages, the main driver of DA was improving efficiency but now it has advanced to improvement in reliability and quality of power distribution [25].

Ever since then, DA has developed and evolved into a recognized concept. Nowadays, with the availability of cost-effective ICT along with the industry-wide momentum towards SG, DA has received renewed attention to create more reliable and efficient distribution systems. Therefore, the concept of DA is based on utilizing evolving computer and communications technology to enhance operating performance of the distribution systems [25] and hence it is the integration of Power, Information and Communications Technology [13]. Although the understating of DA varies widely, but in general it denotes the deployment of automation technologies using ICT for protection, control, monitoring and operation of distribution systems in a real-time mode from remote locations using advanced two-way communication, similar to what is implemented at the transmission level. Thus the term DA implies the utilization of wide set of technologies and approaches for remote operation of distribution networks [26].

The present day DA has received a vast nomenclature from different researchers and authors some refer its related systems as the Distribution Automation System (DAS). Staszesky calls it Intelligent Distribution Automation (IDA) and defines it as DA which takes advantage of advances in computing technology and communication to move the intelligence closer to the problems that need to be solved [27] and this intelligence is reached through the utilization of the IEDs. On the other hand, the DAS can be defined as a system that enables electric utility to monitor, coordinate and operate distribution components in a real-time mode from remote locations [24]. In general DAS includes all devices consisting of a number of components which contribute by some means to the automation and remote operation of the distribution network [28].

Additionally, the ADA system is encompassing numerous integrated applications including distributed computing and intelligent equipment. The sophistication arises as multidisciplinary systems cut across different technical disciplines including but not limited to communications and network engineering, software engineering, as well as electrical/electronic engineering [29] along with the need for all the utilized products to be compatible with each other.

It is worth noting here that the DA is different from SA. SA includes the controlling and monitoring of the breakers at the incoming HV level as well as the breakers at the outgoing MV level whereas the controlling and monitoring of the switchgear at the incoming MV level of the SS comes under DA [30]. A brief discussion about DA is provided in the following sub-sections.

3.3.1 Need for latest version of Distribution Automation

With the increasing diffusion of small-scale power plants i.e. DG/DERs in the distribution network in the future, the structure of the network will become more wide and complex [2]. This is due to the reason that although DG will support local segments of the grid to provide power but it can also result in destabilizing the grid. DA is needed here to precisely manage DER as part of DG to avoid any negative impact and the latest version of DA can also enable utilities for this. The utility companies have comprehensive automation and control capabilities for the transmission network and the same level of capabilities for the distribution network can be reached with the latest DA. Moreover with this growth of DG, the number of nodes in the network also increases thus necessitating a higher degree of automation. These result in the need for DA at these nodes, a lot which in the present day are located at the SS will be mostly in the future.

The implementation level of DA depends upon the need, one of which could be basic upgrading of manual switching scheme with remote control or a fully automated system integrated with IEDs. As DA in one way will assist in automatically monitoring, protecting and controlling switching operations through IEDs to restore power service during fault by sequential events [31], DA is required and its latest version in terms of the new automation principles and techniques is also needed. Thus DA will assist in maintaining better operating conditions and restore the network back to normal operations in case of faults.

Therefore, the latest version of DA facilitates interaction with the distribution system from a central location thus minimizing the dependence on operation and line personnel in the field [32]. This necessitates a DMS to analyse gathered data from all sensors (protective relays, fault location devices, intelligent meters and others) to improve management of the distribution network via information management to prevent the failures and take timely decisions (locally or remotely) following a failure [33]. With the advancement of communication infrastructure for the distribution network, Hydro-

Québec envisions DA beyond the remote control (remote control of major equipment such as CBs, load break switches and capacitors on the distribution grid) functionality. This may be in terms that DA empowers the distribution network to become self-healing and thus more efficient while enabling the implementation of DERs [10].

Another main need for the latest version of DA is for the optimum utilization of existing infrastructure. As part of DA, new concepts of network operation will result in more efficient utilization of the power system. This may be in terms of improvements in operational efficiency which as an example could be achieved by the management of peak loads via new concepts such as DR, new technologies and communications for equipment such as new type IEDs and new system restoration techniques in the form of novel FLISR methods. Thus the latest version of DA can result in the creation of the distribution system of the future where DA and its latest concepts will enable network optimum performance even under varying conditions of power generation while optimizing the operating costs. As part of this, one of the goals of DA is the real time regulation of the loads (one of the ways is DR) as well as generation (one of the ways is energy storage) as well as without (or least) human intervention.

As DA forms a significant aspect of SG, it is briefed in the next sub-section.

3.3.2 Role of Distribution Automation in Smart Grid

The power systems adapt to the future by implementing the intelligent distribution network with the digital grid being the only way forward towards intelligent grids [34]. The digital here refers to the usage of latest electronic, communication and networking technologies whereas the intelligent grid has been used as a synonym for SG. Owing to its potential to revolutionize the way electricity is produced, distributed and consumed, the SG technology can be understood as the ‘Internet for electricity’ [16] and DA is built on this SG technology. As a result DA creates new requirements for remote control for power system when human intervention is not possible or not convenient. Thus in turn assists in realizing the ‘self-healing’ functionality of SG [26] which can be realized making the control of network devices (switches, transformers, capacitors banks and others) in a closed loop form using automation. The automation can work based on recommendations of the distribution optimization algorithms which may be made available by DMS as part of the new DA automated functionality for SG.

With the growing penetration of DG, the power systems become more vulnerable to cascading failures which can result in blackouts and thus the remote controlling of switches (relays, disconnectors and reclosers) through telecommunication link with the NCC becomes essential [35]. Moreover as stated previously, part of the self-healing feature of the SG i.e. the ability to reconfigure networks, divert power flows, isolate faults and prevent overloading of network components is a necessity for optimal operation, which can be fulfilled by DA [28]. Consequently, the development plan for the expansion planning of electric power distribution can be made consistent with the strategic plan towards SG by taking technologies such as DA into account [36]. DA plays its role in line with the SG concept by utilizing the latest developments in the use of sensor and control systems for the distribution network. These can also enhance power quality and reliability by reducing the outage time and by implementing the latest devices (FACTS, solid state transformers and others) at the distribution level.

One of the latest and most talked about concepts of DA for SG is the concept of DR. This may be applied to industrial, commercial or residential loads and these loads could be controlled (to different extents based on the need and contracts) through DR. DA plays a stronger role here to enable Demand Side Management (DSM) by providing systems for information sharing to enable customers to receive real-time pricing signals in order to optimize energy consumption patterns to minimize costs in a dynamic manner. The latest role of DA also includes the DSM functions including Automatic Meter Reading (AMR) and Load Management (LM). The AMR has already been implemented in Finland but the DSM and LM are implemented (to an extent) currently only to industrial customers and the residential customers are planned to be integrated soon as well. The classification of concept of DA is discussed further in the next sub-section.

3.3.3 Categories of Distribution Automation

DA, with its numerous capabilities and applications, can be implemented at different levels of the network [36] and there are different ways to classify the automation functions which are Monitoring, Control, Measurement and Protection. In terms of location, DA functions can be classified into three key categories [31]:

1. <u>Secondary Substation Automation</u>: The DA functionalities at the SS include:
   a) Substation equipment monitoring and control (local and remote)
   b) Transformer protection and Load-Tap-Changer (LTC) control
   c) DG incorporation
   d) Earth fault compensation
   e) Protection coordination
   f) Communication (upstream and downstream)

2. <u>Feeder Automation (FA):</u> The DA functionalities at the feeder include:
   a) Feeder automatic switching/sectionalizing and dynamic reconfiguration
   b) Feeder voltage (through VAR control via capacitor banks and voltage regulator control)
   c) FLISR
   d) Optimal network reconfiguration [10]
      i. Set the optimal switch orders [37]
      ii. Calculate load among the feeder lines which are redistributed [37]

e) Intentional (planned) islanding [10] for island operation of part of the network i.e. Microgrid Management (MM)

Typically, the DA on transformer substation and feeder are integrated to share common monitoring and controlling equipment and devices [31] and this forms the base for the thesis research.

3. Customer (premises) Automation (CA): The DA functionalities at the customer level are quite extensive and include:
   a) Load control
   b) Real-time price signalling
   c) Remote meter reading and billing
   d) DR and LM as part of DSM

Apart from the above mentioned features, there are several other functionalities of DA including but not limited to Outage Management System (OMS), Distribution State Estimation (DSE), Voltage/VAr Optimization (VVO), EV integration, Load Forecast and Modelling and others which are generally located at the NCC.

3.3.4 Benefits of Distribution Automation

Similar to the classification above, the DA benefits categorized as well which include but are again not limited to financial benefits, operational & maintenance benefits customer related benefits and others. There are far too many benefits of DA and it would be impractical to describe them all but the reliability improvement as part of operational benefits is being given the utmost priority as these days the reliability is being linked to financial compensation for the network operators. The reliability measurement techniques are described in section 3.5. The communication need and its implementation for DA is briefed in the next sub-section.

3.3.5 Communication for Distribution Automation

A communication system enables distributed data acquisition, monitoring and control system functions [38]. The communication system is an integral part of DA [31] and it must therefore address today's needs, while providing the ability to add future functionality [39]. For attaining high operational reliability and quality of service with reduced maintenance costs, the MV distribution network needs to be designed with reliable data communication.

Thus for successful implementation of DA, an efficient, reliable and secure communication infrastructure is vital [39]. DA therefore has special requirements for communication channels which include [40]:

1. Reliability
2. Security
3. Construction and maintenance costs
4. Communication channel privatization

The utilization of communications infrastructure and information technologies for DA is primarily to enable remote monitoring and controlling of network elements mainly switching devices. Before the development of DA, the switching operations within the network were done manually by the field crew which required physical patrolling and verification of every switching action even for remote locations. But with the development of wireless data communication for DA, a new opportunity for utilities to expand their system to remote and widespread locations has opened up. The communication media for realizing DA includes but is not limited to:

- Radio Ultra High Frequency (UHF)
- Power Line Carrier Communication (PLCC)
- Optic Fibre cables
- Public switched telephone network and paging services for auto dial-up schemes
- One-way Very High Frequency (VHF) radio for load control
- Internet Protocol (IP) based communication (wired or wireless)

Based on the required functionalities, automation systems have different requirements for networks and most automation systems have operated and a few are still operating independently by using dedicated communication networks and that leads to duplication. For example for a long time, SA has depended on proprietary communications which resulted in a random selection of communication technologies which suited to specific applications and were incompatible to each other. Microwave, Telco lines, Multiple Address (MAS) Radio were some of the most common methods adopted but with increasing number of applications, they led to incompatible communication technologies with a whole new set of problems [41]. DA can learn from SA to avoid this mistake.

On the contrary, IP based communication solutions are non-proprietary and are capable of supporting multiple applications simultaneously over the same network. Beyond the IT industry, diverse applications such as SA, DA and others of the electrical utility industry require reliable and swift communication network [41] and the IP technology delivers cost-effective solution to these needs. For the implementation of the distribution network communication, there is a need of routers in the field and in the NCC i.e. the distribution level SCADA so that all the network devices can be monitored and controlled from one location, thus streamlining two-way communication in the distribution network. The thesis thus focuses on IP as the preferred communication medium and the details for its implementation are discussed later in the thesis.

3.3.6 IEC 61850 for Distribution Automation

As discussed, proprietary protocols have been preferred for use in data transmission and communication applications. Being product or solution specific technologies, these could not be used with other systems due to their incompatibility. This issue led to the formation of a standard for the real time communication of data and signals known as IEC 61850, alongside IEC 60870 for tele-control and tele-protection as part of IEC TC57. Designed for the purpose of establishing a common standard for all substations, the IEC 61850 is a new automation protocol that all manufacturers of all different devices must comply with [42]. The prime focus of this standard has been PS operations and as a result this has found applications all over the world. The IEC 61850 divides inter-substation communication into three levels [43]:

1. Process level, including the I/O devices, intelligent sensors and actuators
2. Bay level, including the IEDs
3. Station level, which includes the human machine interface, the operator´s desk and the interfaces with the substation's exterior

With a library of objects, the IEC 61850 gives flexibility to develop device models for communications and this enables numerous advanced features which augment the field equipment management as well as the compatible integration of applications and equipment. The main benefit is that the application level objects for communications are independent of the physical communications media and networking technology [29] and thus to an extent future-proof with regards to developments in communications media.

The DA applications, with their inherent multi-vendor nature, also require an interoperable environment for common modelling and communication protocol for all devices and vendors. Therefore for DA, the IEC 61850 standard needs some tweaking and this has already started. Originally designed for addressing applications and communications within the PS, IEC 61850 standard has been updated to extend it beyond the substation towards automation at the distribution level [12]. Thus it now specifies the protocol for the interoperability of all the elements from the substation to the point of interface with the end consumers. As a result the applicability of IEC 61850 protocol as a standard has been extended to DA applications for integrating field devices located outside the PS although it was originally intended for intra-substation applications.

With the expansion of the application field of IEC 61850 from the communication networks and systems of substation to the communication networks and systems for power utility automation, the DA field has been given an effective way to handle the interoperability challenges of distribution equipment [44]. While IEC 61850 can effectively model the existing components for DA applications, it needs a few updates for incorporating emerging technologies for network solutions like operation of DG within islands and others. This next section discusses the Fault Management Process within DA.

3.3.7 Fault Management for Distribution Automation

The primary goal of the DA system is fast and precise detecting and handling of fault, to narrow fault coverage and shorten fault outage time while enhancing the quality and reliability of power to customers [45]. This is done by providing information about faults, its detection, indication, location, isolation and supply restoration through network reconfiguration or by correcting the fault via remote controllability.

<u>Process:</u>

In case of fault within on distribution network in the current scenario, the substation feeder protection trips and shuts down the power on the entire feeder. This causes disruption in service to all customers on that feeder. A typical fault scenario and outage time comparison without FLISR implementation is illustrated below in *Figure 3-3*.

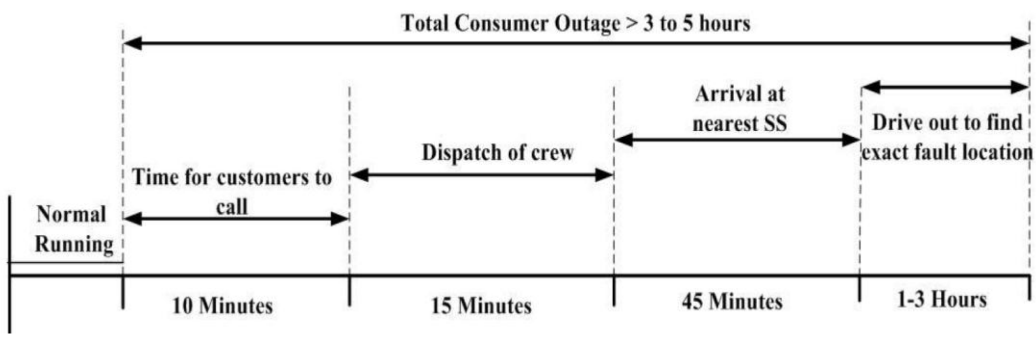

Figure 3-3: Fault Management timescale (without FLISR process)

It can be observed from the figure above that the full fault management process takes approx. 3-4 hours per outage. The process is such that when the faulty feeder has been tripped, the faulty section on the tripped feeder which is a portion of feeder between two switches (SDs or CBs) located at the poles or in SSs, needs to be located. As the feeder in not automated in any form, it cannot communicate with NCC, the remote monitoring of faults as well as control is not possible and this results in long supply interruptions thereby limiting the reliability and security of supply. Once the fault location is traced, manual fault isolation from both sides needs to be done using switches. Finally the fault is fixed and the supply is restored. The supply could also be restored earlier if a backup connection is available for that part of the network.

On the other hand, when this process is automated, often referred to as the FLISR process, the total outage time can be reduced to approx. 1 hour per outage or less as shown in *Figure 3-4*. The outage duration also depends of several other factors including but not limited to: number of remotely controlled switches, number of backup connections, capacity of backup connection and others.

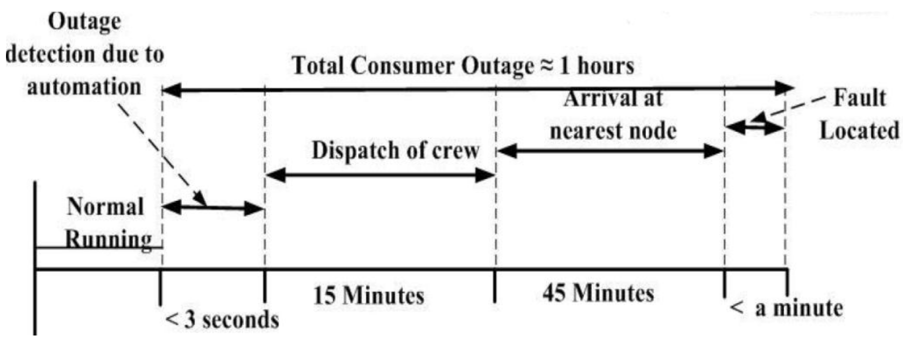

Figure 3-4: Fault Management timescale (with FLISR process)

In this case the fault management process is similar as mentioned before but the manual operation is done remotely (predominantly) using monitoring, protection, control and communication equipment. The number of controllable switches (CBs or SDs) is decided by the DSO based on the number of faults and several other factors. The FLISR process could be centralized: where majority of the decision capability lies at the NCC or it could be de-centralized or distributed: where majority of the decision capability for automation lies at the SS with monitoring and limited control available at the NCC. In general, the FLISR scheme greatly enhances the distribution grid reliability by restoring power to the as many customers as possible in the shortest time [46]. Another example of the time frame is shown in *Figure 3-5* below:

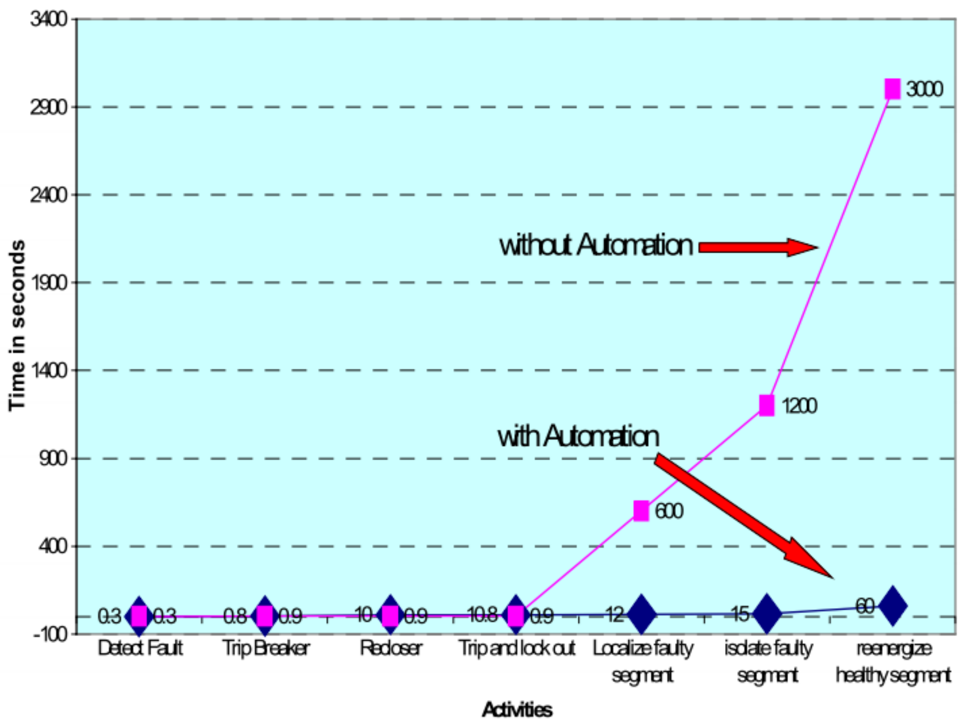

Figure 3-5: Influence of automation on outage time [47]

For integration in the SG concept, Sahin et al. have proposed a DA system that can perform FLISR in distribution systems which incorporate DG and interconnected feeders [48]. In the automated systems, the FLISR process is generally implemented as an application in DMS along with the control being realised from the NCC using SCADA through local equipment (IEDs, switches and others).

This next section discusses how DA can be utilized for the SS.

3.3.8 SCADA for Distribution Automation

Although the communication architecture and network of compatible (interoperable) power system components form the two fundamental components of ADA [49], there is still a need to combine them in a way to receive the desired functionality. The electric utilities have control over the generation and transmission level equipment through the SCADA system but due to the lack of its dissemination into the distribution network, it is unable to provide the same functionality for the DG and DER in addition to the distribution equipment in order to achieve higher efficiency, sustainability and reliability.

The IEDs (with sensors & transducers) which collect information throughout the distribution system, form the foundation of the integrated monitoring system infrastructure of DA [50] and to monitor, coordinate and operate them in distribution network in real-time from NCC leads to the formation of DAS [49] which necessitates the extension of the SCADA systems from the generation and transmission i.e. from PS level to the distribution i.e. the SS level. Distribution SCADA is the foundation of DA and a prerequisite for the realization of DAS [51].

Moreover, for achieving the desired performance and reliability from the distribution network, DA integrates advanced sensors, electronic controllers and SCADA in one integrated system [12]. This leads to the formation of distribution level SCADA which goes along the concept of SG which proposes to adopt and implement the innovations of ICT onto the grid [49], thus taking forward the concept of ‘‘Internet of Things’’ for application in electrical engineering. Additionally, with integration into distribution SCADA, the advanced IEDs enable real-time monitoring of grid condition, allow automatic reconfiguration of the network to optimize the power delivery efficiency and reduce the impact and duration of outages [50], thus increasing the overall reliability of the distribution network.

3.4 Distribution Automation at the Secondary Substation

The SS is a key element in the distribution system and a utility has many of them. Due to its geographically spread, it has long response times for outage recovery and limited overview in operating conditions. This necessitates further monitoring as well as control of the SS to realise optimum operation of the MV network in normal as well fault conditions.

In the current situation, the remote monitoring and control of field devices (recloser and disconnector) is limited to the PS level. In rural areas in Finland, many DSOs have implemented remotely controllable switches located at the branching point of the overhead network. But the need is to extend this capability beyond PSs to all devices at the distribution level The need is to perform the switching (on or off) function either automatically or remotely from the NCC as presently this operation is performed manually or left to fate in case of faults. DA with its variety of capabilities and applications, can be implemented at different levels of the network [52] and SS is one of the most pertinent level. As majority of the distribution devices are present at the SS, it has access to the infrastructure for implementing advanced functionality which makes it the key node to be analysed. Moreover, the automated SS can play a crucial role in the evolution of distribution network towards SG by including a wide range of functionalities in addition to voltage transformation. This is briefly described in the upcoming sub-sections.

3.4.1 Secondary Substation as Smart Node

Within the context of SG, the SSs adopts the role of Smart Nodes (SNs) as they are spread within the distribution network and carry the potential for effective DA implementation. The monitoring, measuring, communication and control features of the SG can be implemented from the SS as an SN. Thus the SN aims to serve as aggregation point for real time management of the distribution network [53] and acts as a distributed system for MV and LV network to take decisions autonomously as well as remotely controlled. Thus, the SN becomes an essential part of the DA system.

Furthermore, the SS is treated as a SN as this is where all the equipment (switchgear, transformer, etc.) are located, or at least in its close proximity and it is prudent to have the local automation there with communication possibilities for remote management. This is backed by its ability to interact with the local devices, sensors and other equipment [53]. As a consequence of its information aggregation, control and communication capabilities, the SN can implement the modularity and extensibility concepts for realizing distributed intelligence as part of DA. Thus by delivering improved continuity of supply, the SN will play a crucial role in the evolution of distribution towards the SG [11].

3.4.2 Secondary Substation Configuration

The SS configuration has already been briefed in section 3.2 and this sub-section provides additional information needed for comprehensive understanding of SS.

The traditional SS are of two types: either pole mounted or housed within a structure i.e. closed cabin or indoor substation. The pole mounted substation is composed for one MV/LV Distribution Transformers (DT) and is referred to as TS. The indoors and closed cabin substations are referred to as CSS and are essentially constituted by three blocks: medium-voltage switchgear, one or more DTs and low-voltage switchboard. If the transformer is missing from the TS but there is still some type of switching device present, then it is referred to as a Feeder Terminal Unit (FTU) which comes under the concept of FA within DA. In this case although it is not a SS, but it can still be considered as a SN as it has the potential for all the functionalities that SN needs as mentioned in the previous segment.

The SSs are traditionally configured as RMU within the urban areas, are unmanned and located within driving distance from the utility's service personnel. The RMU is run as an open ring type of distribution network and the interruption times depend on driving distance and traffic. The main reason for this is that the FLISR process requires operation of several switches in co-ordination with the PS. The outgoing MV feeders from the PS are fully automated using relays and breakers plus remote control by SCADA but the incoming MV feeders at the SS are not fully automated and mainly consist of only manually operated SDs (with or without fuse) with the exception of auto-reclosers at some feeders. This is where DA is needed for transforming the SS into a SN which is explained in the next sub-section.

3.4.3 Secondary Substation Automation Potential

As DA is associated with automation of the secondary distribution network predominantly outside the PS including automation of feeders coming out and covering DTs, Ring Main Units (RMUs), disconnectors, re-closers and consumers [54], thus for realising DA for SS to turn it into a SN some modifications are necessary. Each feeder in the RMU has to be equipped with measuring equipment to obtain both current and voltage signals to the RMU controller, which can then communicate with a SCADA system and other systems for information sharing with the NCC using an RTU. The position indication of each switch (disconnector or breaker) in the RMU can also be monitored and communicated as well to the SCADA system via the controller for enabling network reconfiguration. This also includes the reconfiguration for changing the location of the Normally Open Point (NOP) in the RMU as shown in *Figure 3-6* below:

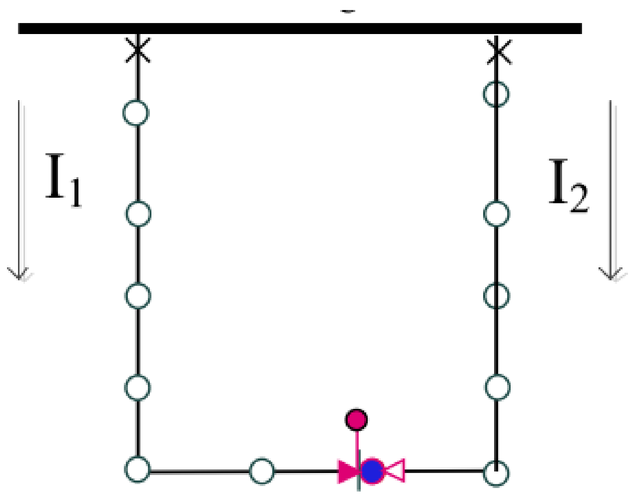

Figure 3-6: MV-distribution RMU configured enabling shift of NOP [28]

In traditional RMU having some automation, the operation is still without communication by monitoring voltage at each switch (at two radial feeders which are separated by a normally open switch) to detect outages and restore loads. This loop scheme has drawback as the control decisions rely only on local measurement and the local field devices have very limited knowledge of the state of the larger distribution network [55]. This can be easily improved by having a communicating device e.g. in the form of an RTU between the local device and the central network and the thesis scope includes this as well. The new capabilities equip the SS with an enhanced visibility of the system to perform the FLISR process autonomously while coordinating with the NCC, thus leading towards the self-healing feature of the SG concept. The current DA involves two types of control [56] for SS:

1. <u>Central control type</u>: integrates field data into NCC through a communication system and performs centralized analysis, control and optimization
2. <u>Local control type</u>: functions without NCC and corresponding communication system and automatically performs the FLISR through predetermined coordination among switches

There are numerous ways in which DA functionalities can be utilized e.g. Antila et al have researched upon DA for MV networks with three solutions [57]:

- Centralised automation model
- Total automation model (combination of centralised and local automation)
- Protection model (only for ring networks)

Coster et al. have discussed a similar solution for the Self-Healing Grid (SHG) which can be implemented in various forms [58]:

- Centralized solution
- Decentralized solution
- Distributed solution

These are illustrated in *Figure 3-7* below:

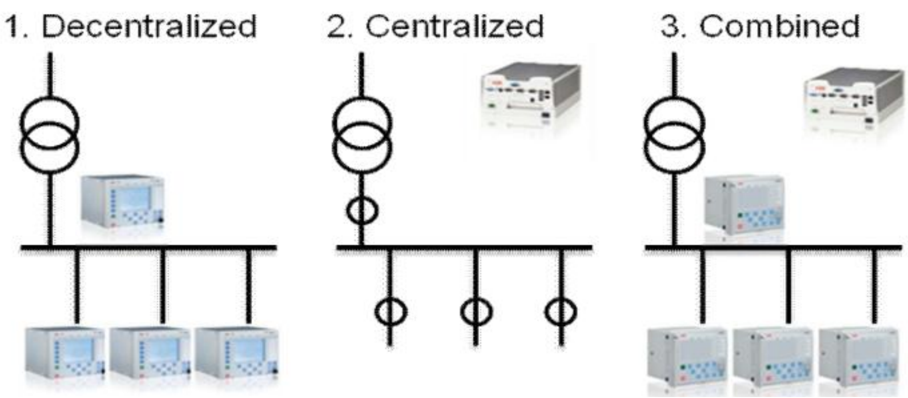

Figure 3-7: Possible architectures for SS [59]

The SG concept involves SCADA to combine the two control types for network optimization without human interference to an extent leading to self-healing capabilities as mentioned earlier. The extent of automation at the SS level defines the capability of the SS to handle fault situations and thus it needs to be equipped with communication functionality for transfer of status indications, measurements, control commands and others as required by the application. Depending upon the extent, this could result in few affected consumers and fast power restoration with less personnel requirement. This extent is defined by the fault vulnerability and the criticality of the load within the SS location which form the key concerns for defining border locations for protecting the network segments which is explained in the next section.

3.4.4 Zone Concept within Distribution Automation for Secondary Substation

The Zone Concept (ZC) in DA is about sectioning the network into smaller zones. Based on loads, load criticality and disturbance vulnerability, ZC systematically divides the distribution network into manageable areas [60]. Thus, the differences in fault vulnerability between one zone and other zones along with the priority of the loads define the required automation level in a zone as explained earlier. ZC is therefore based on the principle to confine the impact of a network fault or supply disturbances to as limited an area as possible [61]. The ZC is described in brief in the segments below:

<u>Process:</u>

The ZC has two key functions: Protection and Control as shown in *Figure 3-8* below:

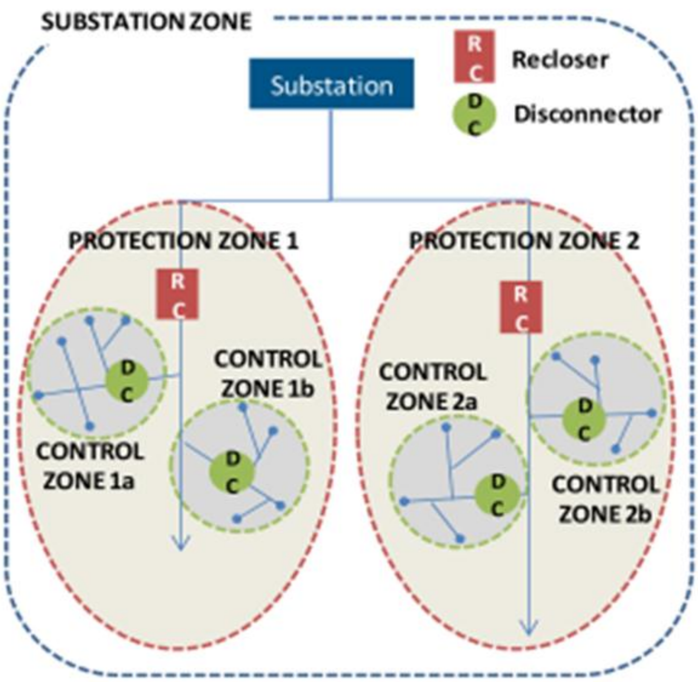

Figure 3-8: Example of zone protection [16]

These are applied to the outgoing MV feeders to create either a protection zone or a control zone based on the capability of the zone divider and the need to secure the supply to areas with substantial and/or critical consumption. Each protection zone with one main incoming feeder has a number of lateral outgoing feeders which can form their own protection and control zones [61]. When a fault occurs in the distribution network, it has impact along the entire feeder including all the connected consumers. ZC works here by integrating protection and reclosing functions. The process works such that distribution interruptions on other sections of the network are prevented by directing reclosing functions and interruptions to the selective parts of the network where there is fault by creating sections or zones.

Components:

For ZC, the key components include CBs and Switch-Disconnectors (SD) as zone dividers for protection and breaking/reclosing or only disconnecting capabilities. Other advance components include line reclosers (CB equipped with automatically closing mechanism), automatic sectionalizers and remotely controlled disconnectors. Based on the requirement, it can also include distributed compensation equipment. For attaining more automation of ZC, communication equipment for communicating with upper level system is also required [60]. This renders remote communication for sharing of status indications, measurements, control commands and other information required by the application. Using the components, there are numerous ways of implementing the ZC. traditionally this is achieved by increasing the density of HV/MV substations or by dividing the network into sections fed by several substations [61]. Furthermore, this restricts any voltage variations or dips to a small part of the network.

3.4.5 Secondary Substation Automation Levels

As the extent to which the automation is applied to the SS varies, it is prudent to segment them into levels which are a prerequisite for the zone concept of DA. Due to the wide functionalities of DA, these levels are based on the specific automation need for SS. Luoma et al. have classified the automation of the SS into four incremental levels based on the functional requirements [62]:

Level 1: Situational Awareness

This level provides the rudimentary functionality of monitoring the SS. This includes low accuracy current, voltage and energy measurement on the LV side with SD status indications which results in rough fault location information and DSE. This information is then transferred through one way communication to the NCC via SCADA.

Level 2: Fault Isolation

This level provides all the functionalities of level 1 and in addition provides control of MV and LV equipment. This control is first done locally with local intelligence for swift network isolation while preventing fault penetration into other zones. The next stage is remote control through two way communication to the NCC via SCADA which provides network reconfiguration for supply restoration to the affected network.

Level 3: Power Flow Management

This level provides all the functionalities of level 2 and in addition enhances the measurement accuracy on the MV side for detailed analysis of the power flow within the distribution network.

Level 4: Protection Selectivity

This level provides all the functionalities of level 3 and in addition provides protection functions with breakers at the incoming and outgoing feeders which make the solution comprehensive for the creation of a zone for DA.

As the management of faults is one of the crucial issues for improving reliability, it becomes prudent to discuss this within the automation context. Based on the equipment at the SS, the Automatic Fault Management (AFM) process can be divided into two basic functional levels [63]:

1. Lower level: has reliable fault indication as the core of fault management
2. Higher level: has full DA capabilities as the core of fault management

The research does not focus on the LV level as similar functionality is obtained from the already implemented smart meters to identify an outage in the LV grid and identify the zone where it has occurred. As the automation is being applied primarily for the improvement of the network reliability, the basics about how it can be evaluated is presented in the next section.

3.5 Reliability Measurement

There have been numerous mentions about the benefit of DA and SG for improving the reliability of the supply but the question then comes about how this can be measured. This can be evaluated based on statistics or based on calculations (reliability analysis). The statistics are useful in monitoring of real performance and the effect of reliability improvement investments whereas the calculation is useful in analysing and comparing the outcome of alternative reliability improvement methods. The basic categorization is based on the following criteria [64]:

1. Interruption Frequency: average number of supply interruptions
2. Interruption Duration: average duration of one supply interruption
3. Interruption Probability: average likelihood of supply interruption based on location

There are several ways of achieving this in the form of numerical indices and the reference is based on either the system or the customer point of view. The relevant indices that are used worldwide and also in Finland, include:

1. System Average Interruption Frequency Index (SAIFI): average number per customer of interruptions of supply per annum that a system experiences calculated as:

$$SAIFI = \frac{Total\ number\ of\ customer\ interruptions}{Total\ number\ of\ customers\ served} = \frac{\sum \lambda_i N_i}{\sum N_i}$$

   where λ_i is the failure rate and N_i is the number of customers for area i

2. System Average Interruption Duration Index (SAIDI): average duration per customer of total interruptions of supply per annum that a system experiences calculated as:

$$SAIDI = \frac{Total\ sum\ of\ all\ customer\ interruption\ durations}{Total\ number\ of\ customers\ served} = \frac{\sum U_i N_i}{\sum N_i}$$

   where U_i is the annual outage time

3. Customer Average Interruption Duration Index (CAIDI): average duration of interruption of supply per annum that a customer experiences calculated as:

$$CAIDI = \frac{Total\ sum\ of\ all\ customer\ interruption\ durations}{Total\ number\ of\ customer\ interruptions} = \frac{\sum U_i N_i}{\sum \lambda_i N_i}$$

$$CAID = \frac{SAIDI}{SAIFI}$$

4. Momentary Average Interruption Frequency Index (MAIFI): average number of momentary interruptions that a customer experiences calculated as:

$$MAIFI = \frac{Total\ number\ of\ customer\ interruptions\ less\ than\ the\ defined\ time}{Total\ number\ of\ customer\ interruptions}$$

These are predominantly annual indices with MAIFI being the least preferred for reporting purposes. With the primary goal of the distribution system being reliable supply and quality power, the reliability indices of SAIDI, SAIDI and CAIDI provide relevant performance measurements [65].

When the reliability of power supply is necessitated at higher levels, DA becomes obligatory for enhancing these distribution system indices [45]. From the DA benefit point of view, research done by Simard & Chartrand has found out that for improving the reliability of the distribution system, the automated distribution line (ultimately DA) is better economically as well as in principle (based on the SAIDI comparisons) than the conventional solutions: increasing network robustness or division of feeder to reduce the number of customers per section [66]. Moreover, with the availability of a real-time monitoring system with the developed DA technologies, there are enormous possibilities for decreasing the duration and affected area for network faults and increasing the reliability of supply [67].

As the DA concept within it with its effect on the network reliability has been discussed in this chapter, it is prudent to relate it to the practical aspects and discuss how it can be realised, which is done in the next chapter.

4. ANALYSIS AND DISCUSSION

With the understating of the basic theory and concepts for the distribution network and the electrical network in general, a thorough analysis of the prerequisites to achieve the practical aspects of SG for DA can now be followed in the upcoming segments. This segment further provides an overview on the network needs, products and solutions available, different feasible intelligence levels, possible types of communication to the NCC as well as necessary components and requirements of future intelligent SS.

4.1 Understanding the broad issue

As already discussed before, majority of the generation locations and transmission networks have already been made almost fully automated which is consistent with the SG vision to promote an augmented and enhanced power grid. But it is the distribution system which is lagging behind although most of the industrial and commercial plants are highly automated. In the past the main issue for this was the availability and the cost effectiveness of the underlying technology but this has now changed with the development of the present day IEDs as part of the advances in ICT which allow control and monitoring of existing devices in addition to several other functions. This is achieved by the utilization of automation technologies for protection, control, monitoring and operation of distribution systems [15] in accordance with the DA concept. As part of DA, the Smart Distribution facilitates the real time and continuous monitoring of the substation and feeder assets for enhancing efficiency and performance in addition to reliability. As DA is the inevitable requisite for the up gradation of the electric power system [51], the shift is in general towards the creation of new active elements or transformation of old passive elements to active elements in the network.

A significant function within it the DA concept is its effect on the network reliability which is being developed and expanded gradually under the DAS model. This is predominantly from the point of view of network faults. The main reason for this is that the reliability has a cost and regulators provide incentives or charge penalties to improve the system reliability. from this point of view, the automation of pole mounted switches in sparsely populated areas may be treated as high priority [47]. But as the underground network within the MV level is increasing due to its certain benefits, the pole mounted configuration is being substituted by the ground recessed CSSs. One of the objectives of this research is to determine the optimal automation degree for the SS for reliable continuity of supply within the Finnish MV network which is briefed in the next segment.

4.2 Finnish Network Context

In Finland, at present 90% of the MV lines are overhead which are very vulnerable to falling trees, a dominant cause for temporary faults [68] and this leads to reduced reliability. This is in contrary to the MV network in Helsinki which is almost all (99.7%) cabled [63]. It becomes essential to minimize the impact of the faults that cannot be prevented by keeping the outage time as short and the affected customers as few as possible. There have been several major development trends towards its solution and two relevant ones for this include: the increase of intelligence of the system & its components and change towards underground networks which are less vulnerable to effects of nature [68]. The first solution is taken care of in this research and its implementation in the MV network is analysed and the second issue being beyond the research scope is not dealt with but is expected to be achieved by the network companies in the near future. The technological options for future networks include: increasing the number of HV/MV substations and using light HV lines, increasing the number of CBs or remote controlled switches, line siting along roads, 1kV distribution, compensation of earth-fault current, Microgrids, DC distribution using power electronics and automation [68].

As a solution for the overhead line MV networks fault mitigation, AR is frequently used in which becomes the cause for short interruptions. This is in the form of High Speed Automatic Reclosing (HSAR) or Delayed Automatic Reclosing (DAR) depending upon the application [69]. Nikander et al. have researched upon the use of Shunt Circuit-Breaker (SCB) for phase-earthing. Although it renders similar effects with temporary earth faults as ARs without the interruptions [69], but it loses functioning in case of two phase-to-earth fault in the network when the SCB tripping has to be reliably prevented. As the CB is in shunt and not in series it cannot be used as an element in network switching or for any other purposes which challenges its cost effectiveness. Moreover as the future networks are planned to be predominantly underground which usually have a permanent nature of fault, this reclosing feature becomes impractical and on the contrary can damage the cable.

The most common networks faults include short-circuit and earth faults which happen as a result of lightning, storms, equipment failure or malfunction and human error. The short circuit refers to the flow of current along an unintended path with no low impedance path. This can happen between two or three phases and the resulting current is typically at least an order of magnitude larger than normal load current due to the low impedance path. On the other hand, the earth fault occurs when one or more of these phase conductors touch the earth which provides an alternative low impedance path to the current to flow. As a result of these faults, the power distribution system interference may occur due to which the supply to the network is lost completely or partially. The number of interruptions due to the earth faults can be reduced by using a compensated instead of an isolated neutral. These fault situations present a danger to the safety and the need is to swiftly separate the failed part of the network from the rest of the network.

Thus electrical network design needs to take the faults into consideration in advance to keep the interruptions low while making sure that the personal safety is not compromised. Therefore mitigation of these faults is a vital issue and the need for solution and systems for automating this is analysed in the next section.

4.3 Needs Analysis

For the implementation of systems to take the distribution network towards SG, a significant investment is required which necessitates the determination of the optimal degree of automation. This optimum level can be defined by one factor and thus it has to take care into account the needs of the network, the technology and the equipment available for implementing it. To make it future proof, the current literature can be utilized to take into consideration the new concepts and products that will come in the near future. For practical aspects, the case studies of projects that have already implanted, to some extent, concepts similar to these have been utilized. All this information leads to a comprehensive understanding of the issue and its resolution is thus possible. All of these are presented in this segment in the upcoming sections.

4.3.1 Network needs

Knowing the network needs is the biggest requirement for finding a solution for it. This has been accomplished by analysing the perspective of the Distribution Systems Operator (DSO). This has been done for Vaasan Sähköverkko (VSV) and the key points from the needs standpoint are summarized as follows:

- The main challenge is to get the location of the fault with high accuracy as this takes a few hours right now in some cases (e.g. with one 20km long feeder through the forest)
- Laying of more underground network as it is less prone to temporary faults
- CBs may be used if they cost-effectively add to the functionality
- More CSS to be used in the future as they are more accessible although a bit more expensive as well
- The number of outgoing feeders from one SS to be reduced and instead smaller CSS be used in large numbers (creation of more controllable nodes)
- Even old SSs need up gradation i.e. not only need for new products and components but to retrofit the old ones as well
- More compatibility needed for new products as the existing CSSs are from different manufacturers and thus have different layouts and different equipment
- Remote operation needed but this need high reliability of operation as well (should work when needed also during loss of supply and not fail due to any reason)

- New products and solutions to be cost effective based on life cycle cost with little need of maintenance
- Networks flexibility for changes in terms of load or generation (DG/DER) addition (in the future)
- The operation and maintenance should be simple including functions such as local or remote operation, parameter setting and others

4.3.2 Manufacturers' needs

A total of three SS manufacturers were interviewed for propose of knowing their requirements namely: Oy Elkamo AB, Finnkumu Oy and Arc-Pro Oy. Although three are not enough to generalize the needs but as the needs vary throughout Finland, no number is sufficient for generalizing. The key functionalities that the SS currently have are:

- Air or SF6 insulated Switch Disconnectors (SD) on MV incoming and outgoing
- Provision for motorised operation (24V DC) of SDs
- Provision for CBs on incoming and outgoing
- Space for a small automation (control and protection) panel

The main needs solicited by the SS manufacturers are summaries as follows:

- Remote operation (control) of SDs
- Communication capabilities for remote operation
- Energy storage (using batteries) for motor operation in case of loss of supply
- DC supply for panel if needed
- Local display and control for local operation
- Protection function using relays
- Detachable antenna for better signal reception (to be placed over or under the roof)
- Earth fault current compensation (in the future)

4.3.3 Lessons learnt from Case Studies

A total of 24 cases have been studied for the purpose of learning from past projects and to apply them to new projects by bringing together any lessons learnt and the effect they had. The key lessons have been summarised in the following points:

- For wider remote areas, rural areas or forests in Finland, radio networks can be used similar to the one implemented in the Rocky mountains (USA) with Radius PDR 221 radios with repeater [70, 71]
- Intelligent remote control systems can be applied to monitor as well control RMUs, pole mounted reclosers and disconnectors, most common in Finland, as has been implemented by Western Power Distribution (UK) using NMS 100 with an additional 'Hit & Run function' which reduces the risk [72]

- The currently used wired communication (PLC and others in Finland) can be made wireless as has been implemented by BKW FMB Energy AG (Switzerland) while complying with IEC 60870 with Radius PDR 121 data radio which has an in-built multi-repeating capability [73]. Similar concept has also been applied in Belgrade by EDB (Serbia) where the radio signal transmission is difficult but has been customized by using repeater stations on the Master-Slave principle [74]
- Retrofit products and solution are needed for updating the existing elements to avoid full replacement (with long asset life still left) in the distribution network in Finland as applied by Northfork Electric, Oklahoma (USA) on reclosers that used Modbus communications protocol and used FastNet RTU to convert that into Distributed Network Protocol (DNP)lan
- protocol to be used by SCADA system [75]. This is also needed to handle a large number of different manufacturers and equipment types as has been done by ADDC (Abu Dhabi) using retrofit actuators controlled by NMS along with FastNet RTU [76]. Apart from being cost-effective, retrofitting existing equipment (with quick deployment) rather than purchasing new, helps maintain supply [77, 78].
- Large scale deployment of solution needs simple approach to roll-out the benefits in a swift and efficient manner as have been achieved by SPEN (Scotland) while utilizing the existing SCADA in parallel with a pre-programmed FLISR process [79]
- To deliver cost effectiveness, the extent of new automation equipment need to be optimized as has already been done by Atlantic city Electric (USA) by applying automation in only a small percentage of the feeders [80] and with varying levels of automation as implemented in United Utilities (UK) [81]
- Optimal automation system needs cost based planning the as to where to automate, what technologies to implement and their intended operation as has been analysed that in some cases even the benefits of loss minimization of the network alone justify the investment [47, 82]
- For solution to the 'where to automate', results from the Smart Grid Investment Grant program of the Department of Energy (USA) have shown that the greatest percentage improvements in reliability occur in cases where the automation is applied only to the worst performing feeders [83]
- Flexibility of control is also a requisite which can be fulfilled by de-centralized automation, as is implemented by Callisto (China) using RTUs supporting IEC 60870-5-101 and 104 protocols for maximum flexibility on the existing and developing communication network [84]. This in United Utilities (UK) have been implemented with automation scheme logic which runs a pre-defined switching sequence for restoring power to the healthy sections [85]. In case of London Power Networks (UK), a similar system originally conceived as a remote control scheme now functions extensively on auto-restoration functions [86].
- Reliability and security while being cost-effective is another requisite for the communication system. This has been exploited by utilizing 3G network with dual

SIM capability for redundancy and economies of scale with public wireless carrier coupled with secured VPN connection [16] with always on operator independent bidirectional communication for real time applications as implemented with GPRS by HPSEB (India), WBSEDCL (India), E.ON (Romania) and ESB (Ireland) along with IEC 104 to IEC 101 conversion [78, 87, 88]. This has also been implemented using satellite connection backed up with 3G or Nordic Mobile Telephone (NMT) (450MHz analog based connection) [89]

- Another solution may also be required for the SS located in forest area in Finland where there is environmental interference. This can be dealt with is a manner similar to SUBD (USA) where 900 MHz wireless broadband through access points have been used [90]. In a way akin to this, VHF wireless links can also be used [91]

Based on these cases, it is quite apparent that the implementation till date has been predominantly for the monitoring, control and communication but a huge aspect of protection has been missed out which plays a key role in the network reliability enhancement.

4.4 Necessities and issues raised in the recent literature

The key concerns discussed within the current literature have been summarised in the following points:

- Conception of equipment which can be connected to the distribution network using the PLUG & PLAY concept in line with the goal for ADA [33]
- For the integration of SS into the smart grid, one of the key requirements is the indication of MV earth faults and short circuit faults [92] with the development of a communication system between the monitoring unit at the SS and the SCADA/DMS systems in the NCC
- The mainstream DA devices need a modular design comprising of industrial grade power module, control module, data acquisition module, communications module and others so that it can be configured and expanded for various measurements depending on the need [93]
- As the electrical system worldwide is very vast and excessively complex to face a revolutionary change, the introduction of new technologies necessitates the capability to interface with old ones for effective implementation [53]
- With the modernization of distribution systems for ADA schemes, there is an escalated need for distribution circuit configurations and reconfiguring capabilities with the associated control and protection systems escalates [94]
- Novel challenges arise with the rapid increase of distributed generation (DG) as the MV network is being used in a different manner than it was initially designed for and the traditional way necessitates increased functionality of bay level protection and control of Intelligent Electronic Devices (IEDs) in the distribution system [95]

- The future distribution system is based on a fully controllable and flexible distribution system exchanging information in addition to the electrical energy between system components [96]
- The need for the current scenario is somewhere between a merely passive SS and a fully automated SSS [97]. This could be in terms of pure monitoring via remote control extending up to targeted load flow control, or the entirety from zero level up to complete smart remote control of the SS [97]
- Using underground cables in place of overhead conductors increases the capacitive earth fault current which necessitates Petersen coils for its compensation [69]
- The degree of automation must be adapted to each network construction to assure the operational capability of the network company [57]
- Investment strategies must provide the optimal network enhancement while minimizing the cost of the enhancement (Dondi et al., 2001)
- As the penetration of the DG/DER as well as the requirement for DSM and other functions in distribution networks increases, more advanced network elements and their conforming control algorithms will be necessitated. These sophisticated automatic control systems are and will continue to be important factors in the mission to deliver high-quality reliable power (Greer et al., 2011)
- Higher reliability in terms of lower average interruption duration and lower vulnerability to environmental conditions thus ideally without any customer outages [68]

The next task is the transformation of this comprehensive information from the needs (highlighted by the manufacturers, networks operators, case studies and literature) to the requirements, which is done in the next section.

4.5 Requirements Analysis

The design of any system is preceded by a formal determination of technical requirements, known as the 'Functional Requirements Specification', which determine its design [98]. These requirements specify the services, tasks or functions which the system is required to perform. These are segmented into two key measures as follows:

4.5.1 Non-functional requirements

The non-functional requirements define how a system is supposed to be i.e. the criteria that define the system operation. These are analysed in more detail in the system architecture section 4.6. These are briefed below:

- Cost effective solutions for reliability improvement
- Modular design for need based functionality choice and future expansion
- Energy storage for Loss of Mains (LOM) operation
- Simple operation and maintenance for large scale deployment

- Flexible and reliable operation of all system components
- Retrofitting for updating the existing elements to avoid full replacement
- Compatibility to interface with old products ones for effective implementation
- Communication capabilities for exchanging information between system components and the related security and safety
- Reliability

4.5.2 Functional requirements

The functional requirements define what a system is supposed to do i.e. the specific system functions based on the non-functional requirements. These are analyzed in more detail in the system/product design chapter 5. These are briefed below:

- Intelligent remote systems with monitoring as well as control
- Protection function (bay level or centralized) for faults
- Accurate fault location (preceded by detection)
- Laying of more underground network
- More CSS use while reducing number of outgoing feeders from one SS
- Provision for CBs on incoming and outgoing
- Provision for local or remote motorised operation (24V DC) of SDs and CBs with DC supply with batteries as backup
- Indication of MV earth faults and short circuit faults
- Development of a communication system between the unit at the SS and the SCADA/DMS systems in the NCC
- PLUG & PLAY concept for component addition of IEDs including power module, control module, data acquisition module, communications module and others
- Use of multiple protection zones in MV networks to minimize consequences of single faults
- Local display and control for local operation
- Detachable antenna for better signal reception

For the fulfilment of the requirements mentioned above, new intelligent and flexible solutions have to be identified and developed [97]. These have been analysed form the system architecture point of view to understand the system functionalities and their function is described through emulation, which is discussed in the next section.

4.6 System Architecture and Emulation

The system architecture here describes the generic conceptual model for the understating of the structure and functions of the system. The emulation imitates the behaviour of the system elements in normal and abnormal i.e. fault conditions for the system under design. All of the information analysed in this segment is utilized in Chapter-5 for designing the product which represents the functionalities and behaviours of the system. Before going on with this, it becomes essential to understand the current design of the SS which is explained in the next section.

4.6.1 Secondary Substation Design

Based on the information gathered from the manufacturers, there are numerous available configurations of the SS. The configuration, size and rating, depend upon the network company for which they are being designed and they could be air or SF6 insulated. These configurations vary throughout Finland but the key design used dominantly is illustrated in *Figure 4-1* below:

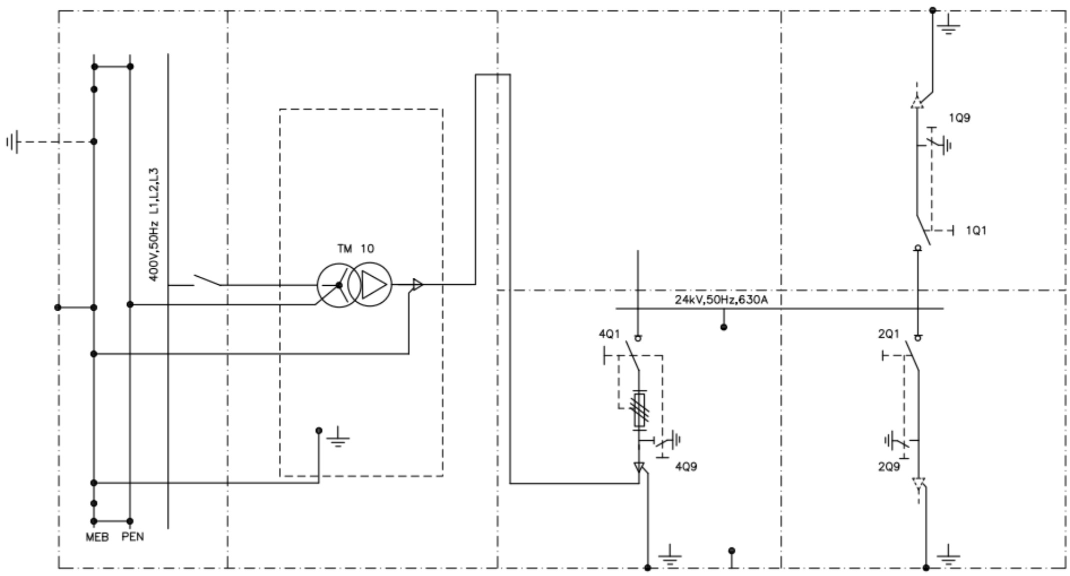

Figure 4-1: SS configuration 2+1 [99]

It is apparent from the *Figure 4-1* above that the basic 2+1 SS configuration has one MV incomer which has a mechanically operated SD and two MV outgoing feeders. One outgoing feeder is fed to the transformer which uses a mechanically operated SD with fuse protection and the other has a mechanically operated SD which goes out of the SS to continue the network and this feeder acts as the incomer for another SS. All of these SDs can be made motorised using motor actuators for local/remote operation or can be replaced with CBs for better protection capabilities. Based on this SS design, the system architecture and its emulation are discussed in the upcoming sections.

4.6.2 System Architecture

From the requirement analysis conducted in the last chapter, it can be concluded that based on the need, the system will have all or some of the following functionalities:

1. Monitoring
2. Measurements

3. Communication
4. Protection
5. Control

The monitoring function is required to know the status of the various elements within the network such as switches, transformers and others. The communication function is necessitated for sharing the monitored information with others devices or straight with the NCC. The protection function is essential to safeguard the network in case of faults. This function necessitates precise measuring of the voltage, current and other parameters. The control function is necessitated to operate the switches when needed and this operation may be manual or motorized. This may in addition be automated locally or via communication with the NCC which then requires energy storage for equipment operation in case of LOM.

The equipment/devices needed to achieve the above mentioned functions include but are not limited to:

- Instrumentation Transformers (Current and Voltage Transformers (CTs, VTs)) or sensors
- IEDs to take inputs from the CTs, VTs and other sensors to perform necessary action e.g. the IEDs could also be a relay with additional features
- Wired (optical fibre, RJ45 or other) or wireless (GSM, 3G, LTE, Radio and others) communication network through modems, routers or repeaters connected to NCC directly or via SCADA
- Motorised setup (SDs, CBs and others) for local or remote operation

The solution used for this research is discussed in the next section where this is emulated along with description of the features needed and utilized.

4.6.3 System Emulation within network

For the purpose of emulation, a network illustration has been in PowerWorld software but as it lacks programmed control command capability; it can only solve network parameters of voltage, current and others and show the effect of switching in real-time but this switching cannot be done by following a pre-defined logic in the software. The Single Line Diagram (SLD) representation of a sample network in RMU configuration is shown in the *Figure 4-2* on the next page.

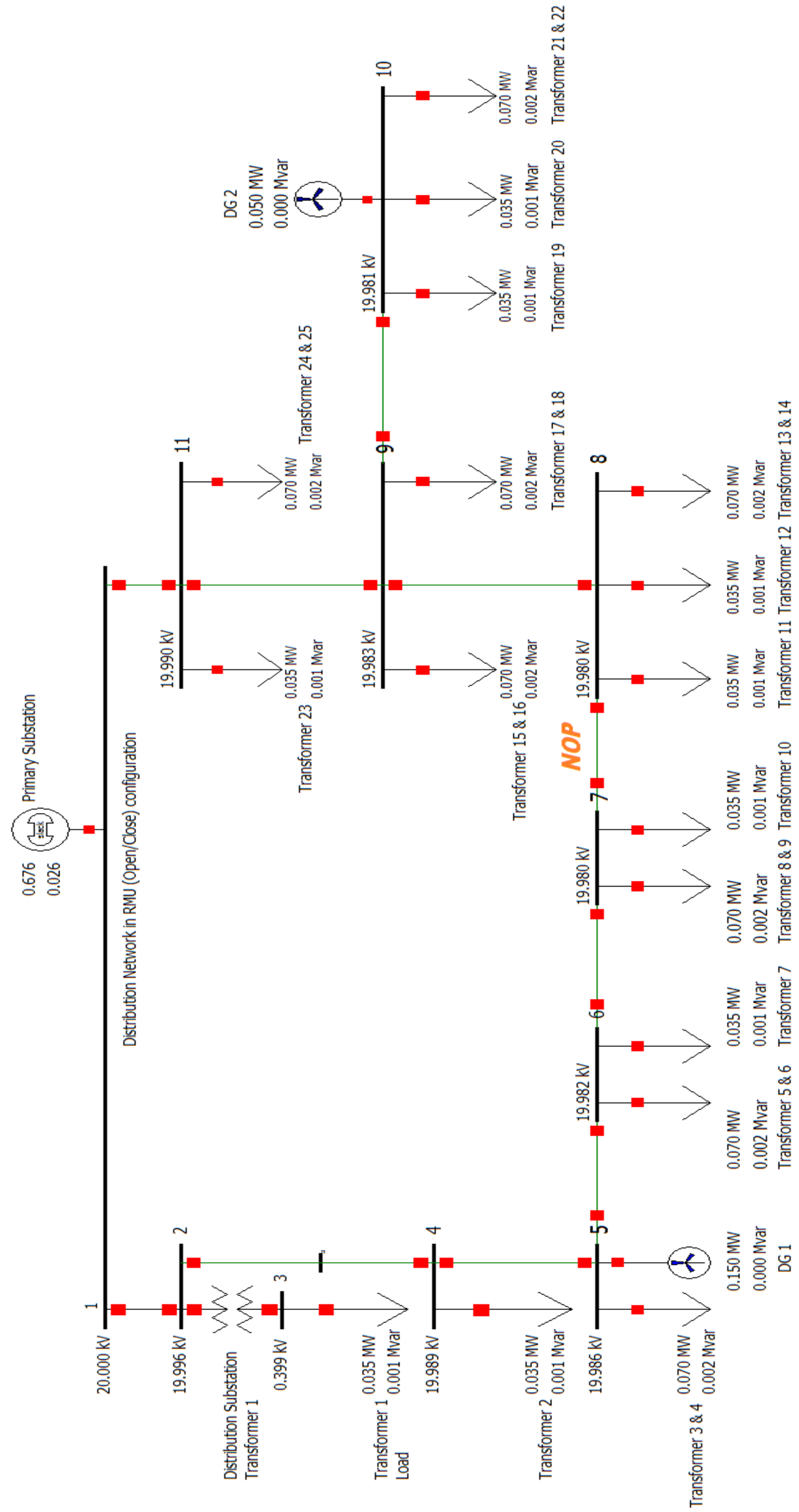

Figure 4-2: Emulated network in RMU configuration

Figure 4-2 shows a MV distribution network in RMU configuration designed in PowerWorld. The bold lines represent the bus bars and the thin ones the MV distribution lines/feeders (overhead or underground) at 20kV. The down arrows represent the loads at each bus bar and the red squares are the switches. There is one main generator feeding the whole network at Bus-1 through the PS and two Wind Generators which represent DG. Buses numbered 2 to 11 represent the SSs and are denoted as SS-2 to SS-11. Each SS has one incoming feeder, one or more distribution (MV/LV) transformers and one or more outgoing feeders. The representation of the transformer is made at Bus-2 only but it is present at each bus as a load.

Though the designed MV-network has a ring structure configuration, the operation is radial by creating a NOP. For this, the switches between Bus-7 and Bus-8 (switch at the outgoing of SS-7 and switch at the incoming of SS-8) have been assigned as a NOP to keep the automation as simple as possible. This is needed especially in case of meshed grid structure as there may be multiple possibilities to restore the grid after a fault has occurred. The NOP play an essential role in restoration procedure of the FLISR process and its automation is thus needed.

> ***Precaution:*** *For utilization of the NOP for restoration in the MV network, it has to be made sure that the LV network is in a radial configuration so that there are no interconnections between the LV feeders being fed from different MV feeders. This interconnection known as the LV-couplings is shown in Figure 4-3 below:*

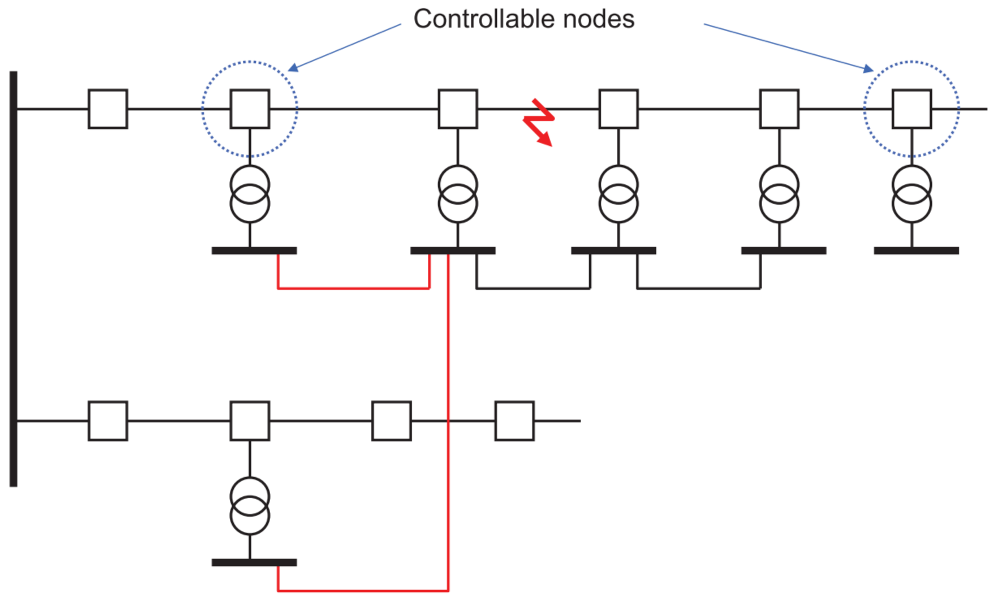

Figure 4-3: LV coupling beneath the RMU configured MV network

> *This was observed by Coster, et al. [58] in a project where the local LV-network had a meshed grid structure. This can lead to a hazardous situation where the faulty location (feeder) is kept energized even after isolation of the fault from the MV network due to the bridge between the LV-couplings. This has to be avoided at*

all costs and consequently it necessitates the LV-networks to be configured in a radial grid structure which becomes a prerequisite for successful implementation of the service restoration process in a RMU configured MV-network.

The emulation here describes system operation using the network shown in the *Figure 4-2*. The emulation also analyses and compares different levels of automation degree at the MV network to evaluate the improvement in the network performance with DA in general. It is worth noting here that as this is part of automation, the functionality of communication, either peer to peer or with the NCC, will be necessitated in all the four cases. Due to the numerous scenarios for implementing automation at the SS, the level concept by Luoma et al. as already explained in section 3.4.5 will be utilized here to an extent for theoretical understanding purpose. In practical cases, the level chosen will be based on the specific automation need for SS by the DSO. For understanding the system operation, the four cases are discussed as follows:

Case 1: Monitoring only

Features: Due to financial constraints, it may not be practical to equip all the SSs with full automation. But there is still the need to know the faulty line/feeder among several others without causing extra disturbance to the rest of the network. In practice this can be achieved by fault indicators which can be implemented based on current measurement only as the voltage measurement at the MV level is not a financially feasible option. The intelligent fault passage indicators may be formed using CTs or sensors and an IED. This case is in line with the lower level of fault management of Siirto, et al. [63] as described earlier.

The reliable fault detection/indication based on local measurements (monitoring) is the most essential part of the fault management process. In practical applications, the fault detection can be simple for short circuit faults based on current amplitude measurement and overcurrent relay principle but for ground faults sum of three phase currents is used for determination of zero sequence component. The directional relay principle based on measurement of zero sequence voltage may also be used if the voltage measurements are also available but as it requires VTs in addition to the CTs, it affects the cost effectiveness of the solution.

This case is in line with the 'Level 1: Situational Awareness' as defined by Luoma, et al. [62] where the continuous assessment of the state of the system is necessitated for various functions.

FLISR Process: In *Figure 4-2*, assume that the fault takes place on the feeder between SS-5 and SS-6. As the power flow is from SS-5 to SS-6, the fault indicators at SS-5 will detect the fault. This information will then be communicated with the NCC by sending the fault indication signal (along with the current measurements as optional*). At the NCC, manual or centralized algorithms are used which utilize the indication signals (current measurements as optional*) obtained from several neighbouring SSs for fault localization and the manual fault isolation and restoration process is started. For this, as the location of the fault is now known, the CB at the PS is tripped (the network on that feeder experiences black-out), the SD at the incomer of SS-6 is opened and the SDs between Bus-7 and Bus-8 is closed manually and the CB at the PS is closed again to restore the service temporarily. When the fault is fully cleared, the service is restored permanently by reconfiguring the network back to its original state. As this is a long process, it is not used if the network is not in RMU configuration, e.g. it is only radial, then in that case the service is fully restored only after the fault has been fully taken care of.

*Depending upon the capability of the IED, the precise fault location may also be found from the current measurements along with the feeder impedance parameters which can result in a faster fault isolation and restoration process.

Case 2: Monitoring with control

Features: In this case, the SS has same monitoring feature as described in Case 1 but in addition it has the control (local as well as remote) capability. This is achieved by having motorized operation of all SDs at the SSs which are controlled using the IED via the NCC and this renders the same results without manual operation.

This case is in line with the 'Level 2: Fault Isolation' as defined by Luoma, et al. [62] where the information provided in the Level 1 is utilized for control. This control can be used for network reconfiguration by opening/closing remote switching devices in the MV network.

FLISR Process: This process is the same here as in Case 1 but the manual operation of the SD is replaced by the remote operation from the NCC for network isolation and service restoration.

Case 3: Monitoring with protection

Features: In this case, the SS has same monitoring feature as described in Case 1 but in addition it has the protection capability. This is by having a CB coupled with a relay (as an IED) on the outgoing feeders of all SSs. This creates zones within the network where the CB is present which isolates the faulty line/feeder from the upstream network without causing extra disturbance to it. The downstream network is however affected temporarily.

This case is somewhere in between the 'Level 3: Power Flow Management' and 'Level 4: Protection Selectivity' as defined by Luoma, et al. [62] where more accurate measurements are made at the SS which enable an enhanced analysis of the distribution network.

***FLISR Process*:** In *Figure 4-2*, assume that the fault takes place on the feeder between SS-5 and SS-6. As the power flow is from SS-5 to SS-6, the fault indicators within the relay at SS-5 will detect the fault and trip the CB on that feeder. The AR feature may be used here depending upon whether it is an overhead or an underground network. This information will then be communicated with the NCC (using DMS/NIS or similar system) and depending upon the relay capability the precise fault location may also be found. Thus in this case the network is protected automatically from the fault by isolating it using CB. But the full isolation (opening of the SDs at the other end of the feeder) and service restoration process is still manual and same as explained in Case 1.

Case 4: Monitoring with protection and control

Features: In this case, the SS has same monitoring and protection features as described in Case 3 but in addition it has the control (local as well as remote) capability. This is achieved by having motorized operation of SDs at the incomers of all SSs which are controlled using the IED (which also has relay capabilities). Although a better option is of having the CBs but due to financial constraints, it may not be practical to equip all the SSs with them but having motorized operation of SDs renders almost the same functionalities of the CB except for the protection function in a cost effective manner. Moreover, the remote-control option of the switching devices within the SS helps in realising the benefits of the ZC with the future possibilities of new separate zones as the network expands.

This case is in line with the ‘Level 4: Protection Selectivity’ as defined by Luoma, et al. [62] where protection functionality with full capability for zone formation is added to the SS.

FLISR Process: In *Figure 4-2*, assume that the fault takes place on the feeder between SS-5 and SS-6. The whole fault identification, localization and isolation process is the same as explained in Case 2 except the service restoration process (switching On/Off of the SDs) in this case is remote from the NCC and no personnel has to visit the SS. Thus the fault is isolated by remotely opening appropriate line switches. The service is then remotely restored to the un-faulted segments of the network by re-energizing it via backup (one or more) sources using remote controlled tie switches (NOP). This case is in line with the higher level of fault management of Siirto, et al. [63] with advanced DA functionalities as described earlier and can thus implement the full FLISR process.

This remote operation has several options e.g. Chouhan, et al. [100] have proposed and researched upon multi-agent based system which uses centralized and decentralized methods in conjunction with each other to make up for the disadvantages of each method. The remote operation can as well have different running modes as which are: manual-confirmation, auto-confirmation and assist-mode [63].

Safety feature: *As the control mentioned here is local as well remote, the local feature is predominantly for use in troubleshooting process when the remote operation has limitations. In this event as all actions have to be done in a safe and sound manner, personal as well as environmental safety is of paramount importance. For this the IEDs in all the automated SSs are proposed to be equipped with a local/remote switch and when maintenance personnel enter an automated SS the IED is put on local mode manually. As a result of the local mode, no unexpected switching actions (due to remote operation) can occur and hence safety is ensured.*

4.7 Reliability Analysis

As reliability is the key issue for which the solution is being explored, it becomes pertinent to understand how it enhances it. The reliability measurement gives the expected number and duration of outages at each load point in the network as well as the overall reliability indices specifically SAIFI, SAIDI, CAIDI and MAIFI. Although, the reliability analysis results are based on statistical calculations, its effect is seen as an improvement in service and resulting economic savings.

These measurement indices used for reliability analysis have already been discussed and it is apparent that calculating them needs information about the network configuration, the number of customers on it and its fault vulnerability (based on past statistics) as a prerequisite. As the product under design is customizable and is intended to find applications in wide areas, no specific network is chosen for reliability analysis. But there is still the need to evaluate its effectiveness towards reliability and this is accomplished by utilizing the data available from earlier studies and analysing how it relates to the solution here based on the four case cases as discussed in the last section. All of these, in a way assist in the improvement of the reliability of the service by the considerate management and coordination of the processes involved in the FLISR process.

As the quantification of reliability assessment is pertinent to the cost-benefit analysis of smart substation implementation, the results of the analysis done by Rodriguez-Calvo et al. (2012) have shown that the automation of MV/LV transformer substations does indeed improve SAIDI and SAIFI indices. The indices portray strong reduction rate for low and medium degrees of automation with the saturation effect setting in as the degree of automation increases [11]. Hence, it would not be incorrect to assume that the smart SS can provide very high reliability levels with the optimum level of automation applied to ensure maximum efficiency, technical as well as economic.

4.7.1 Reliability need at the MV network

As the product being designed in the research is for application within the MV network, it is essential to justify its need. Coster, et al. [58], in their research within the German network, have established that the outages in the MV grid contribute majorly to the SAIDI as illustrated in *Figure 4-4* below (MV is MS in the figure).

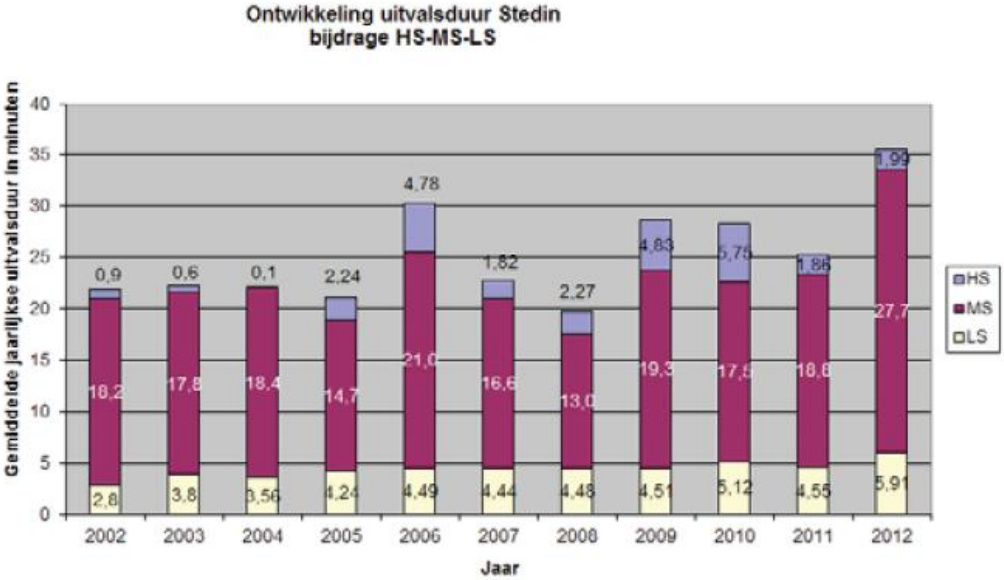

Figure 4-4: Contribution to SAIDI by LV, MV and HV network (11 year timeline) [58]

Thus enhancing the reliability by decreasing the impact of the MV grid will result in the reduction of overall SAIDI. This can be achieved in the best possible manner by the application of DA at the SS level [58]. The statistics for interruption minutes within Finland are shown in the *Table 4-1* below:

	Interruptions minutes lost per customer per year										
	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Transmission	2.12	2.10	2.02	2.10	1.50	1.55	2.7	5.0	6.9	1.3	2.6
Distribution	123	103	180	145	103	129	96	279	366	175	343

Table 4-1: Interruptions in transmission and distribution networks [101]

The SAIFI for Fortum in Finland in 2013 was 1.74 (1.01 in Sweden [102]) compared to 1.40 in 2012 [103]. Similarly SAIDI in minutes for Fortum in Finland in 2013 was 220 (103 in Sweden [102]) compared to 103 in 2012 [103] and SAIDI in minutes for Fortum in Finland in 2013 was 115 (92 in Sweden [102]) compared to 61 in 2012 [103]. These statistics indicate a strong need for the automation at the distribution level for reliability enhancement out of all the other options of underground cabling, maintenance and others. The next issue now is the level of automation needed at the SS level which is discussed in the next section.

4.7.2 Automation extent for Reliability Enhancement

As the application of the product is an investment which will last for a long time and will not be changed soon, it has to be justified according to the network needs, the investment budget allocated and current regulations while utilizing the latest evolved technologies based on their economic implementation while keeping the customer's needs and load growth within context.

For the discussion over the level of automation needed at the SS level, the four cases discussed in the last section are utilized here. Simard and Chartrand [66] have done similar studies where they have made comparison of the different scenarios of the automation level. These are relevant for this research as the levels compared are quite similar to the ones proposed. These results of these comparisons were prepared using Hydro-Québec's in-house software that simulated the effect of different ways of implementing automation levels. The input to the software was the real outage data collected for two years from approximately 2,800 feeders of the Hydro-Québec's distribution system. The output of the software was the recomputed reliability indices based on nine scenarios of implementation, five of which are shown in *Table 4-2* below with their percentage improvements along side:

Scenarios	SAIDI	SAIDI improvement	SAIFI improvement
1 – Remote fault indication only	**1.96**	**4.6%**	**0.00%**
2 – Optimized recloser installation (1 per feeder) without remote control	**1.98**	**3.6%**	**3.55%**
3 – Remote control of actual switches and breakers	**1.61**	**21.6%**	**0.00%**
4 – Remote control of actual switches and breakers and addition of breakers when needed	**1.60**	**22.1%**	**3.55%**
5 – Remote control of actual switches and breakers, addition of breakers when needed and automatic reconfiguration	**1.56**	**24.0%**	**3.55%**

Table 4-2: Evaluation of different scenarios of implementing automation

For the generalization of the comparisons, contrast between the different scenarios was made using the same outage database and hypotheses for all.

Case 1: Monitoring only as discussed in the last section can be compared to the Scenario 1 shown in *Table 4-2* above. It is apparent that it results in minimalistic improvement in the SAIDI level and no improvement in the SAIFI level as the frequency of the fault is not being affected by the monitoring. Thus this level of automation implementation independently does not prove to deliver improvement worth the costs associated.

Case 2: Monitoring with control discussed in the last section can be compared to the Scenario 1 shown in *Table 4-2* above. In this case as only the control is changed, the operation becomes fast and can be done remotely but there are no other changes. Thus it is apparent that it also results in minimalistic improvement in the SAIDI level and no improvement in the SAIFI level as the frequency of the fault is not being affected by the monitoring or the control. Thus this level, as well, of automation implementation independently does not prove to deliver improvement worth the costs associated.

Case 3: Monitoring with protection discussed in the last section can be compared to the Scenario 3 shown in *Table 4-2* above. It is apparent that it results in strong improvement in the SAIDI level and a small improvement in the SAIFI level. This is due to the fact that the duration as well as the penetration of the fault within the network is being affected by the isolating it from the fault using the CB. Thus this level, as well, of automation implementation independently does prove to deliver improvement worth the costs associated in a very effective manner.

Case 4: Monitoring with protection and control discussed in the last section can be compared to the Scenario 5 shown in *Table 4-2* above. It is apparent that it results in the strongest improvement in the SAIDI level and still a small improvement in the SAIFI level. This is due to the fact that the duration as well as the penetration of the fault within the network is being affected by the isolating it from the fault using the CB and in addition the network is being reconfigured automatically (or from the NCC remotely) to re-energize the affected network using the NOP. Thus this level, as well, of automation implementation independently does prove to deliver improvement worth the costs associated in the greatest possible manner.

The scenarios 2 and 4 here does not directly link to any of the cases as it is somewhere between a combination of Case 3 and Case 4. The analysis of the different scenarios has showed that implementing additional local automated system has resulted in improvement in the SAIDI and SAIFI in a positive way.

Now with regards to the decision for the extent of automation at the SS, the research proposes an ideal system could include a few SSs where higher level automation has been employed and many other SSs with several feeders where only monitoring is done i.e. a system having SSs with the automation levels of the different cases discussed in the last section. This has been confirmed by the research done by Coster, et al. [58] where three concepts with varying levels of automation were compared for the SAIDI and SAIFI measurements. The SAIDI and SAIFI graphs presented in *Figure 4-5* are relative with respect to the reference cases.

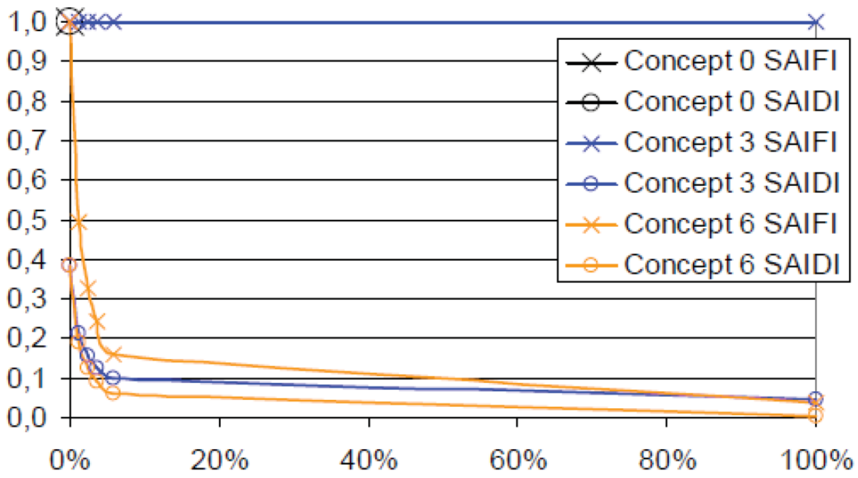

Figure 4-5: Impact of SAIDI and SAIFI for various degrees of automation [58]

It is apparent that automating a few SSs results in a substantial reduction in SAIDI and SAIFI and any additional increase of the automation level leads to negligible improvement in these indices. Thus it can be concluded that as the full automation extent of all the SSs is expensive, it is not cost effective approach. As is reflected in the *Figure 4-5* above, it is not necessary to automate all SSs in a network to achieve a significant reduction in SAIDI and SAIFI. Thus as proposed above, a system having SSs with the automation levels of the different cases will result in significant SAIDI and SAIFI reduction while the average investments per automated SS will remain worthwhile and practical. The final decision to implement these different automation levels for the network DA system rests with the network service provider based on their experience of that network in order to reap maximum benefits at the lowest possible costs.

In general, it can be concluded that the extent of automation depends on the state of the SS considered, the costs of retrofitting or customizing, the criticality of loads and on the fault density of the network [63]. As the effect of the new product on the reliability improvement of the network has been discussed with the extent of automation needed for it, the product design is discussed in the next chapter.

4.8 Analysis of previous Studies

The purpose of analysing previous studies is to gain understanding from them about the approaches that have been used to deliver novel methodologies for the problems while avoiding the same mistakes and any replication of the work. This has been discussed in brief in the following segments.

4.8.1 Distribution Automation Implementation

To begin with, it has to be understood that the MV network nodes as the DA terminals act as the initial point for data acquisition and control. For this, DA acts as a united system which operates and coordinates remotely to use all distribution network components in a real time mode as a distribution engineering tool [104]. Thus they have a pertinent role to play in the distribution network fault analysis and processing, network optimization, reconstruction and others [93]. As a consequence, the DA system construction follows international, domestic and industry standards to create distribution management platform, integrate information system and achieve comprehensive application of information interaction for network regulation and control [105].

With DA as an exploration of the power automation field of expertise [106], some authors discuss about the adaptability of DA to the existing solutions and products available rather than the other way around. But in turn for the appropriate development and implementation of DA, not only should it adapt to the distribution network characteristics, but also to the relative technologies of SG including smart terminal units, advanced communication, energy management and others [107]. In line with this, Chia Hung et al. have advocated the use of Multi-Agent Systems citing the flexibility and adaptability with a rapidly changing environment due to the distributed nature, modularity, and ease of implementation [108] as the advantage. But due to this the system becomes decentralized and there is no designated controlling agent present. This results in the need for central computing facility with communication capabilities at the NCC to handle large amounts of data from the distributed elements.

The electrical power network can be defined as an undirected graph with vertices portraying the network elements including substations, switching stations, overhead line, overhead cables and other elements whereas the graph edges presenting the switches [109]. The presence of these switches is a bliss as with an optimum design of the network, the switches provide the capability to reconfigure the network to connect or disconnect the network elements in such a way which leads to improved required parameters. With regards to the network reconfiguration, Xuejing & Qian have researched and done pilot studies on control integration in distribution network and have found out that through the application of dynamic network topology analysis, the forecast and analysis of the distribution fault can be achieved and optimized distribution network operation, maintenance repair and other aspects be taken care of [110]. Further, utilizing flexible switch location for optimal configuration of distribution network can improve efficiency of the operation and restoration and improve the reliability of a DAS [111]. This flexible switch location refers to the location of the normal open point (tie switch) of the ring mains configured network. With ADA, all the switches of the network can have remote controllability and can thus be switched in a way to make its position as the tie point so as to distribute the load evenly between the two radial segments of the ring network.

For analysing the network topology and its effect on DA implementation, Tan et al. have researched upon the modelling method based on information sharing which can improve the efficiency of Automated Mapping (AM), Facilities Management (FM) and other DA applications including but not limited to topology analysis, fault handling, load transfer analysis and others [112]. This information sharing model is very easy to implement once the information from various SSs is available in real time. For a practical understanding of this, Marttila et al. (2009) have studied a segment of the rural Finnish MV network and have analysed that for improving the reliability of electricity distribution, increased investments are profitable in most cases studied in the research and predict that there would be new light modular substation in the network under consideration in the future with the possibility of using CBs to divide MV feeders into smaller sections [113].

4.8.2 Functionalities evaluated

Several researches have focuses on the functionalities based on the network needs but these are very diverse and cannot be generalized but still a preliminary analysis of these is essential. The functionalities can be categorized into four main segments: monitoring & measurements, communication, control and protection. Note that the monitoring here also includes the measurements.

<u>Monitoring and measurements</u>: This forms the most basic but critical aspect of the automation process. For this within the SS, the measurements and alarm functions are carried out by a measurement (for currents and voltages) and monitoring (for temperature and equipment) unit part of IED along with sensors and/or instrumentation transformers. The IED could have simple protection capabilities to trip a CB or operate the motor actuator of the SD/s or other devices based on the monitored/measured quantities. Consistent with this Smallwood et al. have researched upon using the Automated Faulted Circuit Indicators sensors for feeder automation [114]. But these sensors are mere indicators and do not provide real automation capabilities unless there is provision for reclosing the open points between feeders for restoring normal operation. Similarly, Hyvarinen et al. (2009) have tested a similar pilot system but with only measurement capabilities without much control with two types of SS: remote monitored and remote controlled.

<u>Communication</u>: For the remote operation just mentioned, it becomes essential to have communication capabilities. For this as there is no fit-for-all situation application for the communication technology type to be used [3], the advantages and disadvantages of each must be evaluated to determine the right technology for application. A few of the options for this are summarized in the *Table 4-3* below:

Media	Transfer rate
Wired	
Fibre optics	2 Gbps - 3 Tbps
Local Area Network (LAN)	10 Mbps - 1 Gbps
Data services in public networks	$\leq$ 1 Gbps
Leased line	9,6 kbps - 2 Mbps
Integrated Services Digital Network (ISDN)	64 kbps - 128 kbps
Dial-up line	$\leq$ 64 kbps
Power Line Carrier (PLC)	15 bps - 36 kbps
Wireless	
Satellite link (GEO-system)	$\leq$ 10 Mbps
Radio link	$\leq$ 2 Mbps
Radio telephone	1200 kbps
VHF/UHF narrow bandwidth data radio	9,6 kbps - 19,2 kbps
Global System for Mobile Communication (GSM)	9,6 kbps
General Packet Radio Service (GPRS)	40 kbps
Enhanced Data rates for GSM Evolution (EDGE)	400 kbps
High Speed Packet Access (HSPA)	10 Mbps
Long Term Evolution (LTE)	100 Mbps

Table 4-3: Communication media with data speed capability [115]

The wired medium has already been researched and implemented quite a bit but for the wireless media Tae-Il et al (2008) have researched and developed DA technology using CDMA wireless communication network [3]. Consistent with this, Vaishnav et al. have researched upon DA system architecture using GPRS as well as CDMA communication network and analysed the techno-commercial feasibility of using mobile phone networks for DA. Due to the large investment requirement, the utilities are not willing to deploy their own communication infrastructure, which leads to the usage of public mobile phone networks as a necessity as well as an advantage due to the fact that the further investment for the continuous network monitoring, maintenance and upgrade are also avoided [116]. An example of the communication system within one network utilizing different communication types is shown in *Figure 4-6* below:

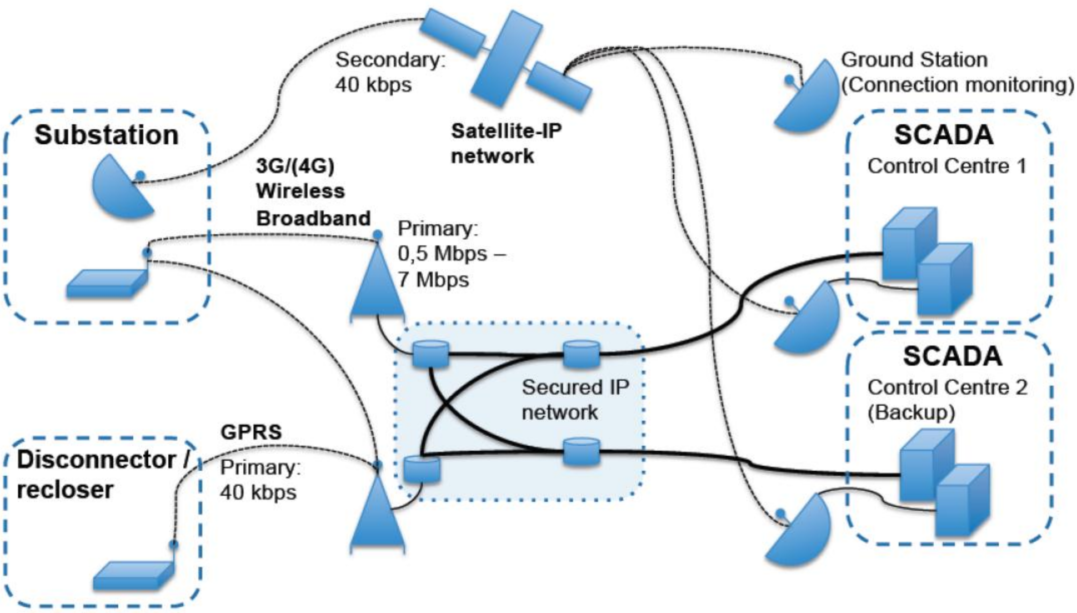

Figure 4-6: Field communication system used by Elenia (Verho, 2013)

With regards to the protocol for communication, Kasajima et al. have researched and developed a similar product realize the DA system based on the advanced RTU with TCP/IP interface for advanced functionality and transmitting the data to the NCC via the optical fibre network [117]. In contrast to this, Zhang et al. have researched upon the modelling scheme for power grid data sharing between transformer substations and the control centre based on IEC 61850 and IEC 61970 [118].

<u>Control</u>: Once the communication is established between the SS and the NCC, the control can then be performed remotely. This is the next step for automation and via the remote control of switches, more elaborated self-healing through local or centralized control can be achieved. This leads to a higher degree of automation and intelligence for networks [119]. The remote controlled SDs and fault indicators as part of feeder level functionality, form part of extended DA [120]. In Finland, the remote control of disconnectors was implemented in late 1980's and has been widely used since. These disconnectors are predominantly switched automatically in case of faults based on local processing (based on the operation of on-site fault detectors) without any communication with the upper level [120].

Based on the remote operation of switches, Du et al. have researched on the distribution network application system with focus on topology application where an intelligent switching order graphic guided switching-order generation in real-time context is realized [121]. This leads to a lot of gathered information which has to be managed and for this Makinen et al. have researched on the concept of development of systematic procedures for data management for improving distribution network design [122]. Moreover, based on the system conditions and operational requirements, a real-time selection of critical loads can be achieved by the flexible configuration of static transfer switches [123]. Murthy et al. have also assessed the reliability impact of automatic feeder reconfiguration for smart distribution purposes and have found out that this leads to improved reliability due to enhanced capability in decision-making with fast communication regarding fault detection and classification [65].

Protection: Achieving the protection with the control functionality can assist in implementing the concepts of zoning and sectioning of the distribution network in case of faults. This can isolate the faults and trap it by creating a fault zone by turning on and off a combination of switches as all the control to achieve this can be available for execution remotely through NCC via SCADA. To be precise, the CB with/without auto reclosing creates a protection zone whereas the remote control of the SD creates a control zone which is essential for isolating the fault and de-energizing the network for maintenance purposes.

Rodriguez-Calvo et al. have designed a topology where the smart SSs are connected to the MV network through normally closed manual switches with protection capabilities using CBs at few selected points [11]. In a similar research, a DA switch (based on SD but not a CB) was designed to provide a remote switching function with low energy operating mechanism with a control battery for multiple/repeated switching operations [124].

4.8.3 SCADA Integration via NCC

DA comprises of the operational control of the grid through communication with remote units and their control based on the remote monitoring of currents and voltages in the distribution grid [125]. For the remote operation, there is a need of connecting the NCC to the controlling points on the distribution network which is currently not fully implemented. This has the potential to reduce overall maintenance costs (due to reduced number of maintenance calls to remote locations), increase control efficiency and reliability of the network. This can be done using the existing SCADA for information interaction between transmission level and distribution level data. This can ensure open and functional interface to realize integration between power distribution, dispatching, fault mitigation and other aspects [126]. This way the real time information from several nodes on the network can be displayed graphically by SCADA or DMS system using an existing NIS system for further control. Overall, this integration to an existing SCADA system can result in realizing maximum benefit with minimum investment.

As part of DA, Korea Electric Power Corporation has developed two types of DAS, one is small DAS which has the functions of remote control (remote data acquisition and remote setting) and the other is large DAS with the structure of duplicate servers and feeder automation, simulation and loss minimization in addition to small DAS functions [127]. In Finland, a system similar to the large DAS is already functioning at the transmission level but the need for a small DAS at the distribution level is yet not fulfilled. By having the operational control of the MV disconnector (present at SS) remotely at the NCC, the decision of reconfiguration can be made using SCADA. This achieves the purpose of distributed information gathering via monitoring and operational control while maintaining the central intelligence without the need for distributed intelligence.

As automatic feeder sectionalizing and restoration is a core application for DA, the FLISR algorithms and their processing capability available at the SCADA level carry out complex network self-healing [128]. Using existing SCADA leads to the creation of self-healing capabilities for the MV grids for DA, without requiring additional functionalities from the deployed equipment in the network. The only functionality needed is to report information (data/status) and act according to implement control commands from SCADA. This way, the initial steps of the FLISR are done at the bay level and this information is reported to the NCC but if the fault still remains, the control goes to the NCC and the appropriate action is instigated via SCADA.

4.8.4 Cost-benefit analysis

Last but the most relevant aspect is the cost. Due to the large number of devices to be monitored & controlled and spread over a larger geographic area in the distribution network, the key design parameters for its automation are driven by the cost [54]. Therefore the pricing of the products and solutions have to be justified for their implementation and a rudimentary analysis of the costs becomes essential. Additionally, with the development of new technologies and products, the potential for the possibilities increases while in addition the costs for installing new functionality in SS decreases [4]. The cost of assets as a percentage in given in *Figure 4-7* below:

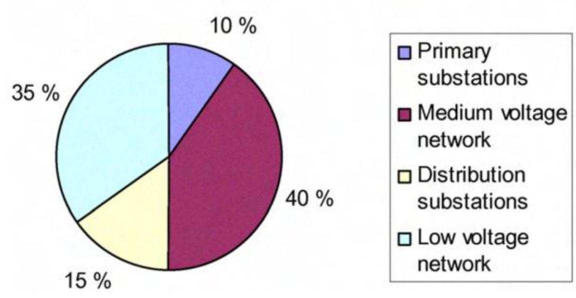

Figure 4-7: Typical asset value share of the distribution network in Finland [95]

The costs of individual components and overall price of the product has to justify the need as well as the resulting benefits. This is relevant as the number of SS is quite large and the every increase in price is multiplied by this factor which may result in a sign fact amount for the DNO. E.g. there are 2,400 SSs within HELEN's (Helsingin Energia) network compared to 20 PSs. This results in a ratio of approx. 1:120 which is substantial by any means. An example of this is from Viola Systems as illustrated in the *Figure 4-8*. The system here has optimised number of remotely controllable SDs (mentioned S) and

CBs with auto-reclosing mechanism (mentioned RC) with communication. The average cost of the automating the network for remote fault mitigation is compared with the penalties that incur due to a manually fault mitigation and the payback time is also calculated. The more are the number of CB's the less is the fault penalty but more is the automation cost. The optimised numbers are shown as a percentage and their location within the network.

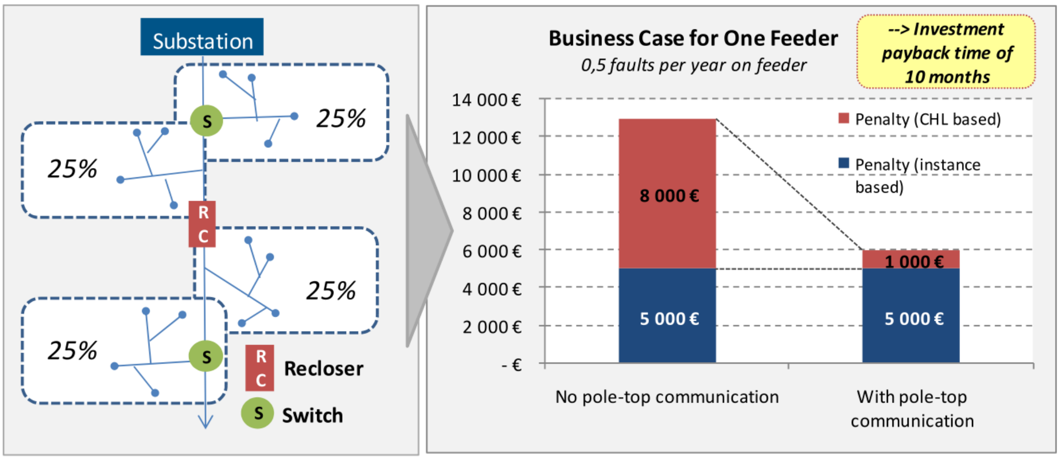

Figure 4-8: Viola business case for one automated feeder [88]

Based on savings from penalties from the sample network configuration as shown in the *Figure 4-8* above, the investment breakeven point has been calculated to be around 10 months which is significantly small and is feasible.

As a matter of fact, as an increasing number of DG is added by DSOs, the situation necessitates the deployment of automation in SS in very short timeframe. Moreover, the increasing demands on operational profitability are causing high pressures for cost effectiveness. The requirements have been thoroughly analysed and discussed in this chapter along with the emulation of the system for it and their effect on reliability. Centred on these, a concept for the customizable product and the components needed for it based on the currently available market products is presented in the next chapter.

5. PRODUCT DESIGN

With the requirements of the new product at hand complemented by the concept of its operation within the network through the emulation, the development process for designing the product can now be started and is laid out in the upcoming segments. As the product comes under the field of electrical engineering as well computing due to its automation capabilities, it integrates hardware as well as software for its functioning. The hardware and software need each other to fulfil their potential as without the software, the hardware functioning is very limited and without the hardware, the software would not be able to function at all. Both of these are discussed in the upcoming segments.

5.1 Design and Pre-Engineering

The design approach provides a guide towards the overall goal of the design. A combination of two approaches is utilized here which are as follows:

5.1.1 Customizable Approach

The product is under design for its application within the SS but as there are more pole-mounted recloser units than SS within the Finnish MV network, it must be able to customize to that application for its automation as well based on the needs. This could for example even be just the basic control and communication capabilities for pole mounted reclosers with the NCC for enhanced automation. Thus the product is for the creation of SNs rather than just SSs as discussed in section 3.4.1 earlier.

The need from the technical point of view is to design it in such a way that all the monitoring is done in detail, however the cost-effectiveness restricts this and thus does not justify implementing 100% monitoring for all SNs in the MV distribution network. Therefore the implementation level can be customized based on the classification done by the utility centred on the network topology, the network customer profile, the criticality of that node as well as the relevance of the monitored data. This requires a modular cost effective approach where ‘plug-in’ hardware can be installed based on the requirements and the financial capacity [77]. Thus by delivering a customized product/solution, the precise and valuable functionalities can be rendered to the utility which further leads to less complexity and costs for installation and future maintenance. The basic product design approach can then be classified into three design categories to make it customizable:

1. Modular
2. Compact
3. Scalable

The modular concept is the key here. This approach is applied to the IED such that all the functionalities needed by the IED can be added by making specific modules for them e.g. a current module, a communication module and so on. This then leads to achieving the 'Plug and play' concept as any of the modules can then be fitted to the IED without must calibration. The modular approach also makes it more compact as all the features come within the IED and it also makes it scalable as new module can then be added based on the growing needs to enhance capabilities. The modular approach is discussed in more detail in segment 5.2.

5.1.2 Retrofit Approach

The product is under design for its application within the SS as well as the pole-mounted recloser units as already mentioned before, but all of these already exist, although the pole mounted configuration is being replaced by ground SS, they need a product that can be fitted into their existing configuration. Implementing distribution equipment reform is one of the key essentials for automation [129]. Consequently it gives rise to the need for a retrofit approach.

The retrofit approach e.g. could include the addition of some local intelligence in the existing SS (or pole mounted recloser) or the addition of motorized operation of the manual SD with communication capability for remote operation. The approach is again customizable but the basic idea is that it should be compatible to upgrade the existing equipment (may even provide provision for solutions without any component replacement). Using this method, different elements of the automation for SN creation can be applied with small cost-efficient steps which allow distribution utilities to implement network automation in several steps with or without the replacement of existing equipment. Therefore it would be incorrect to conclude that the retrofit approach makes the design concept cost-efficient while enabling a step-wise approach towards the creation of SNs. It has to noted here that the key requirement for the retrofit solution is fast and easy installation so as to minimize the shutdown of the SS. The changes needed for the retrofit approach are discussed in more detail in segment 5.2.

5.2 Hardware Aspects

The hardware includes the physical components that make up the system and these components are discussed in the upcoming segments.

5.2.1 Intelligent Electronic Device

The main hardware required for the product is the IED. The development of the IEDs took place in the form of development of the numeric relays, which are software based embedded systems, as an upgrade from the old electronic based solid-state relays. The

IEDs are integrated microprocessor-based devices which have been in use since the late 1970's and early 1980's in mission-critical applications. The IEDs such as intelligent relays find application as a key component of the protection system apart from other applications within the system.

The functionalities for the SN creation that have been discussed in the last chapter link closely to the ones that are provided by the modern day intelligent relay but some functionality is provided by other IEDs which are designed specifically for those purposes. The practical solution needed is in between a combination of those IEDs. A comparison of the four such IEDs from different manufacturers has been conducted and a brief is given in the Appendix 3. A lot of features are linked to the ones that are provided by feeder protection relays of different manufacturers and any of them can be used here for developing the solution however due to the collaborative relation between Arcteq and VEO, the Arcteq AQ-F215 (feeder protection IED) will be used here as reference for designing purposes and the modular approach is explored. The IED is shown in *Figure 5-1* below:

Figure 5-1: AQ-F215 feeder protection IED by Arcteq

Although this particular product and manufacturer is chosen as the reference but this in no way undermines the approach of the solution which can be realized by using a similar product by another manufacturer. The various features needed from the IED and AQ-F215's compatibility to those functions are discussed in the following sections.

5.2.2 Modules and Components needed

Based on the functionalities obtained from the requirement analysis combined with the proposed system architecture conducted in the last chapter, it can be concluded that the product for the designed system will have the following features as the modules along with the additional components:

1. Monitoring and measurements

For the SS, the first need for automation is the monitoring capability. This here also includes the different measurements needed for implementing this capability. Thus the monitoring includes:

- Feeder/s monitoring: This includes the MV level current and voltage (optional can be alternated with LV level) measurements for all/specific incoming or outgoing feeders at the SS. As this is implemented to improve the reliability, the level of this mechanisation is based on the needs and costs involved.
- Equipment monitoring: This includes the monitoring of all/specific equipment existing inside the SS. As this is implemented to improve the maintenance, the level of this mechanisation is also based on the needs and costs involved.

As precise phase current measurements are available from the CTs and compromised but calibrated voltage measurements from the LV side of the SS transformer, the following monitoring capabilities (with their ANSI codes) can be enabled:

- Current Transformer Supervision
- Fuse Failure (60)
- Disturbance Recorder
- CB Wear

IED modules: For feeder monitoring, AQ-F215 has a module for current measurements (phase currents as default and residual current as optional) as well as a module for voltage measurements. As the voltage measurement at the MV level is impractical (due to VT being expensive, large in size and other issues), only phase current measurements are utilized and the residual current can be obtained from them. Although a few of the less relevant functionalities are lost, this makes the solution more cost-effective. The IED may also need to be coupled with a memory for storing the measured values for further analysis especially the statistics for the fault situations. AQ-F215 has a disturbance recorder as the default feature for this need. For equipment monitoring, AQ-F215 has the capability for monitoring CB position indication, wear, SD position indication and all of this is scalable by using a digital I/O module for controlling SDs using dry/wet contacts.

Please refer to the AQ-F215 instruction manual for details on these modules’ features.

Other components needed:

CTs: (3) needed for feeding measured currents (transformed down to the relay levels)

VTs: (3) needed for feeding measured voltage (transformed down to the relay levels) but only in case the need is supported by the financial capability

**Although the voltage measurements are expensive to be obtained from the MV side, but in case there is a transformer available at the SS, the voltage measurements could be obtained from its LV side which can be calibrated for use. The AQ-F215's voltage module can take LV input directly (secured using LV fuses) as it is made to handle voltages up to 630Vrms continuously.*

Sensors: for current and/or voltage measurements (as an alternative to CTs and VTs) but in a different manner

**The issue with using sensors for MV measurements is that the number of available IEDs compatible with them is few and the manufacturers have designed them based on the standards for instrument transformers in the absence of the ones specifically defined for MV sensors. Due to their still-evolving nature, low cost-effectiveness, their use is needed be carefully considered to avoid their replacement in the future is case their effectiveness is not met by the needs [130]. Therefore the use of sensors for the scope of this research is excluded.*

Wiring: for connecting the components to the IED

Fuses: for protecting the IED from surges in the incoming signals from the CTs and the voltage measurement from the LV side

2. Communication

As majority of the system modules/components have some electronic characteristics and are connected to each other to achieve the final level of system functioning, they have to interact to transfer information, commands and other relevant information and data. This necessitates a communication module to provide this capability for peer to peer communication or communication between SS and NCC. The communication between SS and NCC is more relevant as the peer to peer communication is also achieved via the NCC. The overall need is to integrate communication needs in a single pathway, supporting various technologies and security mechanisms. In addition as the SS are located at geographical distances, they need cost-effective wireless communication with the NCC to avoid the costs of creating wired network.

IED modules: For communication, AQ-F215 has fixed communication connections RS-485 (2-wire) and RJ-45 (serial fibre and redundant Ethernet cards as optional) for system integration and service bus communications. The missing component here is the wireless capability but this is under the design process to be made as a module can then be integrated into the AQ-F215 as an option.

Other components needed:

Wireless Gateway: (1no.) to enable wireless communication (GPRS, EDGE, LTE, Radio or other) signal transmission to the NCC (in the near future this will be available as a module for integration into the AQ-F215 as mentioned before)

**There are different products by different manufacturers for this but as an example Viola Arctic GPRS Gateway is chosen which connects the IED (using Ethernet connection to Wireless Gateway) to NCC via wireless GPRS network using public network operator (SIM card).*

Figure 5-2: Viola Arctic GPRS Gateway

M2M Gateway (located at the NCC): (1no.) to enable wireless communication signal reception from the IEDs (via the Wireless Gateway)

**There are different products by different manufacturers for this but as an example Viola M2M Gateway is chosen which connects all the IEDs (using Ethernet connection to Wireless Gateway) at different SSs to NCC via wireless GPRS network using public network operator (SIM card).*

Figure 5-3: Viola M2M Gateway

The whole communication approach is summarised below:

IED-> Ethernet-> Wireless Gateway-> GPRS-> M2M Gateway-> Ethernet-> NCC

RTU: not needed!

**As the key purpose of the RTU is to interface objects, do the acquisition of data parameters from objects local/substation, transmit them to the NCC and control objects using commands from NCC (e.g. using SCADA) [38], these are being done by the IED itself and the wireless capability has also been added as just explained before. Thus the need for RTU vanishes as the remote monitoring and control of field equipment is enabled via two-way wireless communication using the IED and the related components.*

The specific software aspects and the protocols for communication are described in detail in segment 5.3.

3. <u>Protection</u>

As precise phase current measurements are available from the CTs and compromised but calibrated voltage measurements from the LV side of the SS transformer, the following protection capabilities (with their ANSI codes) can be enabled:

- Current Protection Functions
    - Overcurrent (50/51), Earth fault (50N/51N), Directional Overcurrent (67), Directional Earth Fault (67N), Transient Earth Fault (67NT), Unbalance (46/46R/46L), Harmonic OC (50H/51H, 68), Breaker Failure (50BF/52BF), Restricted Earth Fault / Cable End Differential (87N), Line Thermal Overload (49L)
- Voltage Protection Functions (basic level protection using LV measurements, needs MV level VTs for more precision)
    - Overvoltage (59), Under Voltage (27), Neutral Overvoltage (59N)
- Power Protection Functions (basic level protection using LV measurements, needs MV level VTs for more precision)
    - Power (32/37)
- Frequency Protection Functions (basic level protection using LV measurements, needs MV level VTs for more precision)
    - Frequency (81O/81U), Rate Of Change Of Frequency (81R)
- Arc Protection Functions (<u>optional</u> depending on the SS kVA rating)
    - Arc Protection (50ARC/50NARC)

**It has to be noted that although the above mentioned protection capabilities are being utilized, the IEDs have more protection functions available as default which can be accurately used if voltage measurements from the MV side are available. The issue is that as the LV side is in grounded star configuration, it cannot provide the positive sequence component, but it can* *provide the reference for the voltage which can be used to obtain directional (earth fault) characteristics from the relay. The phase shift due to the Dy configuration of the transformer can be offset within the relay settings. While this voltage measurement cannot calculate the precise power and energy calculations, it can still calculate the power factor and provide full protection from all types faults.*

IED modules: AQ-F215 comes with all of these protection capabilities as default and does not need any specific module for this except for the arc protection card which is essential if arc protection is opted.

Other components needed: No additional components needed!

4. Control

As the SS has the capability for remote control, there needs to be options for choosing the control mode: Local, Remote or Off (prevents both local and remote operation and allows only manual operation). In addition there could be a Hit & Run function (coined by Netcontrol) which allows the user to select a local switching operation (delayed by a configurable time) and move away safely from the equipment before the operation takes place.

For object control, input signals in the form of binary inputs or software signals or Generic Object Oriented Substation Events (GOOSE) messages or real time protocol (IEC 60870-5-104) could be utilized and output signals in the form of close/open commands could be utilized. This is for the motorised operation of the SDs as well as for other equipment.

As precise phase current measurements are available from the CTs and compromised but calibrated voltage measurements from the LV side of the SS transformer, the Auto-reclosing Function (ANSI code: 79) for earth faults can be enabled:

IED modules: AQ-F215 comes with all of these control capabilities as default and does not need any specific module for this. But for controlling more components with the SS, additional Digital Input or Digital Output modules can be used.

Other components needed: No additional components needed for the control panel but there are two additional components would be needed for the transformation of the SS in an SN: motor actuator for the SD at the incoming feeder as well as replace of the SD/s with CB/s at the outgoing feeders.

5. Power Source

As majority of the system components within the SS require a reliable auxiliary voltage supply and with the addition of modules/components, (which have some power consumption) the rating of the auxiliary power system increases. If the auxiliary voltage fails, like in case of faults, there is no power in the SS but it still has to function to maintain the IED and the Wireless Gateway function. An energy store supplies the components for time periods reaching from few minutes to two hours which necessitates stored energy in the form of battery which further necessitates battery chargers and their size depends on the power demand from the components. In addition to these, there is the energy consumption for motorised SDs inside the SS.

IED modules: For power, AQ-F215 has a DC or AC power supply provision but the missing component here is the battery charger or an even advanced Battery Management System (BMS) however this is under the design process to be made as a module can then be integrated into the AQ-F215 as an option.

Other components needed:

Battery: (1no.) to enable operation is case of loss of auxiliary power

**There are different products by different manufacturers for this but as an example Powerizer LiFePO4 battery (24V, 10Ah) is chosen based on the calculated power need.*

Figure 5-4: Powerizer LiFePO4 battery

Battery Charger: (1no.) to enable battery while preventing discharging beyond the minimum charge level to extend battery life. The IED is kept informed of battery status via a number of remote status alarms, which are also displayed on the local operator panel (in the near future this will be available as a module for integration into AQ-F215 as mentioned before)

**There are different products by different manufacturers for this but as an example Powerizer Smart Charger (designed for LiFePO4 battery) (25.6V, 6A) is chosen based on the calculated charging capacity needed.*

Figure 5-5: Powerizer Smart Charger

Space Heater with thermostat: (1no.) to make certain that the cabinet temperature (and dehumidification) is thermostatically controlled to ensure battery temperatures are kept within the manufacturers' operating tolerances and in addition battery charging may be temperature compensated to ensure battery health

> **There are different products (e.g. PT 100 resistance thermometer as temperature sensor) by different manufacturers for this and any one can be chosen.*

6. <u>Modules/components for future needs</u>

There are numerous other modules that may be added in the future but a few of them are briefed below:

DG Integration module: With the development of SG, the scenario is changing as the consumers are becoming mini producers by exploiting the available RES and the need is to integrate this production into the network and this is achieved either at the LV or the MV level, the provision for the HV level is already provided by Fingrid. AQ-F215 has a synchro-check (ANSI 25) as an optional feature which can be used in case of DG integration at SS. Moreover, the monitoring and control of inverters from the wind power and photovoltaic systems may also be necessitated to ensure power quality in the future along with energy storage capabilities within the SS.

Volt and VARs Control: With DG integration, there will be bi-directional power flows within networks which have been originally designed for uni-directional power flows which can lead to congestion and problems in regulating the voltage. This may need capacitors (banks) for MV feeders and or MV/LV transformers with tap changers within the SS situated at critical network points with their remote supervision and control.

Petersen Coil: for **e**arth fault compensation systems at the MV level to limit the arcing currents during ground faults

Island operation: exceptional network control and supervision algorithms could be utilized by the IED in co-ordination with the NCC to create micro-grids using DG to feed customers directly in case of major outages

All of the abovementioned hardware components including the main IED (except the future ones) would be fit into a panel, the design of which is discussed in the next section.

5.2.3 Panel Design

As all of the above mentioned components have to be fit into a panel, its design and pre-engineering, based on the component dimensions and specific requirements, becomes essential. Based on the dimensions of the individual components the elementary drawing for the SN panel is illustrated in *Figure 5-6* on the next page:

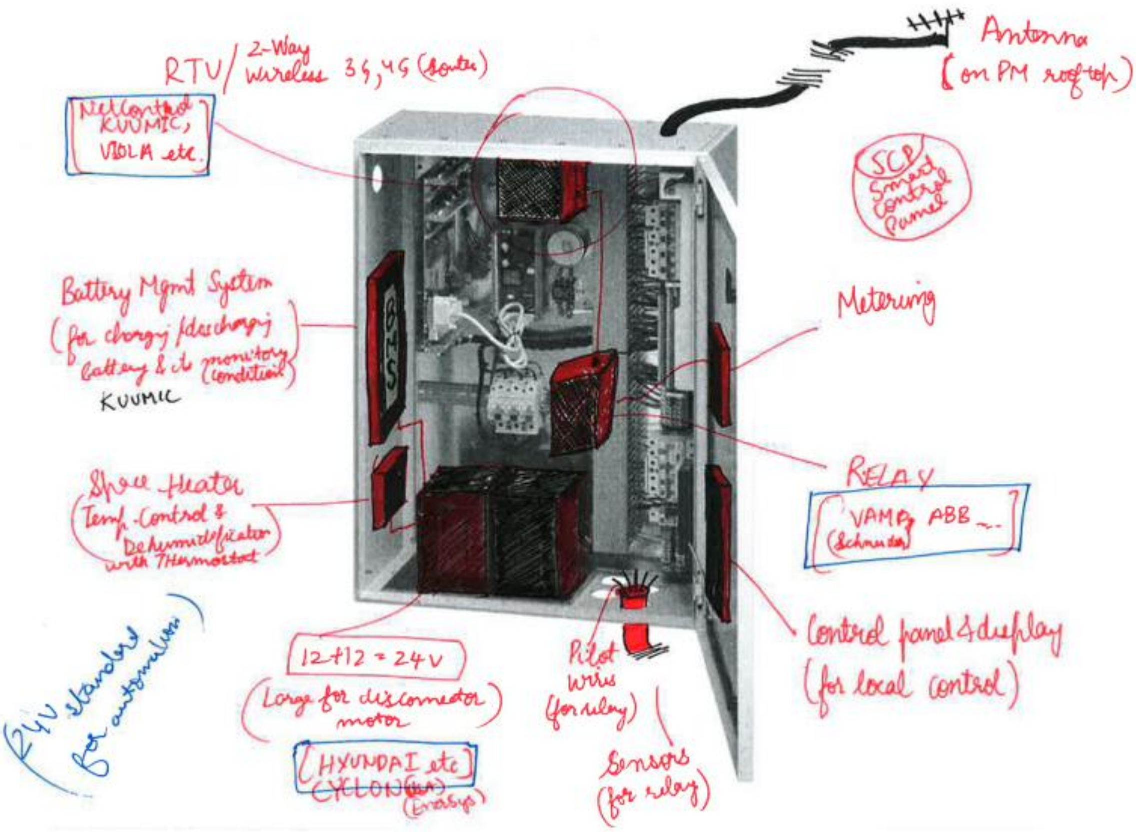

Figure 5-6: Initial sketch for SN Panel

5.3 Software Aspects

The software includes the programs and related data that provide the instructions for hardware what to do and how to do it. This is in addition to the software needed at the NCC level for self-healing and network reconfiguration which is defined and designed by the utility company. The various software aspects of SN panel are discussed in the following sections.

5.3.1 IED programming

As the key component for the SN is the IED, there needs to be provision for its programming based on the network needs (control, protection and other). This may be provided via a user for local panel configuration and programming by using a software suite with a Human Machine Interface (HMI) or NCC with SCADA interface.

5.3.2 Communication System

The communication system requires comprehensive service, versatile communication and data transfer options within which all the SNs can be connected to the NCC. There are two types of data in a SS [42]:

1. Critical: control of devices that act as the smart breaker, the controllable transformer and observe values such as current and voltage (directly affect substation operation)
2. Non-critical. acquisition of auxiliary values on the operation of the substation, such as environmental or transformer temperature and status of switches

As a result of monitoring at all the SNs, more data becomes available at the NCC. Although this enhances the situational awareness but it can become an obstacle if the data handling capability is not developed [55]. Thus the communication system plays and important role for the automation at the SS level. The key aspects of the communication system are as follows:

Communication Medium:

Due to the location of the SNs, the wired communication with the NCC is possible if wired connection is feasible and in other cases only wireless option is possible and can be utilized via the GPRS gateway mentioned before as it fulfils all the data size and speed needs cost-effectively. This could also be replaced by an EDGE or an LTE (or unlicensed radio transmission with narrower bandwidths in case of remote locations) version but the communication remains wireless. Larger investments in terms of network establishment and maintenance are avoided by utilizing the existing public communication network. Within the NCC, wired serial communication (e.g. Ethernet) is used to connect IED to GPRS gateway.

Communication Protocol:

For supporting different DA functions, open and standard protocols need to be implemented. This is accomplished by using IEC-61850 along with IEC-60870-5-104 (101 as well if there is any old equipment). Within the SN, the communication protocol between GPRS gateway and the IED could be IEC-60870-5-101/104 based, whereas the communication between SN and the NCC can be made effective by using IEC60870-5-104 protocol which could be then tunnelled over the GPRS using VPN. In fact, the IEC-60870-5-104 protocol is an extension of IEC 101 protocol with a few changes and it uses an open TCP/IP for network interface.

Within the network, each wireless gateway of the SN is assigned an IP address by which it is identified in the network. The M2M wireless gateway present at the NCC has the capability to assign static IP addresses to create a private network (not available to the external internet). This further enables the IED configuration to be done remotely from the NCC using the same physical session used for SCADA communications.

Apart from discussed IEC-60870-5-101/104, IEC 61850 can be potentially used to develop this application by using it as the communication protocol in the future. This can be realised by the utilization of the Logical Nodes (LN) which are smaller units taken from the protection and control functions. The LNs can be used for various protection, control, measuring and monitoring functions as well as the control of physical components such as transformers, CBs, SDs and others. As the IEC 61850 standard requires that communication between the devices be wired via fibre optic or cable, its utilization for remote application becomes limited but the wireless LAN for it is being researched right now and may be possible in the near future.

Communication Security:

To maintain high communication security level for the time-sensitive data, robust data encryption protocols coupled with internal firewall becomes crucial. This can be realised by establishing Virtual Private Network (VPN) connections between the SN and the NCC.

6. CONCLUSIONS

This chapter provides the final conclusion of the research. This is put into sections which describe how the study has been successful in terms of the fulfilment of the research aim and objectives along with the practical implications of the study and the recommendations for future further studies in the field.

6.1 Fulfilment of Research Aim

The research has reviewed and examined the approaches of automation and its implementation with the distribution network. The study has researched practical methods for linking/integrating the existing equipment at the secondary substation level to the new designed product. This had led to the designing of a solution in terms of a customizable product as well as its operation within the distribution network as shown in Figure 6-1 below:

Figure 6-1: VEO SNP for SS

The designed product can be used for purpose of automation to render remote monitoring and control of distribution network. The aim of the research is accomplished in terms of the investigation of the extent to which the automation can be applied to the distribution network in a need based manner. This has been verified with the future Smart Grid approach and the extent has been shown to be very high with the future needs. The feedback and suggestions received through various interviews and discussions have been utilized to effectively implement them for improving current level of automation at the distribution level, if there exists any. The aim has been accomplished by achieving all the five objectives that were laid down in the beginning of the research which are described in the next section.

6.2 Fulfilment of Research Objectives

The scope of the research was made clear and precise with breakdown of the aim into defined objectives. This facilitated the in-depth analysis and thorough investigation of each of the objectives while making use of the primary as well as the secondary research. The realisation of each of the objectives is presented below.

The first objective was to study the various components and analyse how they can be used utilized for switching on or off a part of the distribution network, in case of faults or for network power flow optimization. This has been examined through the extended literature review by analysing the journal articles, technical reports and papers of product companies and network providers. The results were confirmed and made thorough and comprehensive through primary research in the form of interviews and discussions with experienced personnel from the mentioned organizations. The primary as well as secondary data was analysed through a rigorous methodical process as explained earlier. This explicitly identified how the system can be modified in the perspective of the integration with other devices and solutions based on different communication technologies.

The second objective was to study and obtain information about the existing products and components presently available in the market. With the requirements made apparent through the literature review using the secondary research with the verification through the primary research, the thesis has provided a discussion over the various tools and techniques of proving automation at the distribution level. This was in terms of new modules and components that can be retrofitted into the new product which can be installed into the secondary substations to make it smart to allow full management of the SS features including monitoring, measurement, protection, control and communication functionalities at the MV level.

The third objective was to study the products and analyse how they can be used utilized for communicating the signals from the transformer substation to the control centre with new distribution level or existing transmission level SCADA. As the product is integrated into the automation network as an additional element, it communicates upstream via two-way communication with NCC using SCADA managing information and allowing remote operation. The communication system has been discussed in section 5.3.2 and the 3G network has been found to be the most suitable in urban and rural areas while the radio network to be used in regions of poor 3G connectivity. Moreover, as the device has been designed with a modular and scalable feature, to provide a standard solution for different topologies of secondary substations, a standard communication method was necessary which has been fulfilled.

The fourth objective was to create a preliminary specification needed for designing and integrating the product modules in a compatible way. This was necessitated as the product has several tasks right from receiving measured electrical quantities (voltages and currents), monitor the status of equipment, operate the switch when fault conditions occur and exchange information with the NCC about the operating status. As the product can operate not only on the basis of local measurements but also by means of communications with the NCC, its needs remote control and automation functions in order to achieve the network status information and also modify the network configuration based on need to improve reliability.

The fifth and the last objective was to design a customizable product for the all the above mentioned features by utilizing the analysed information. This has been discussed in detail in chapter-5 and the product features are also mentioned therein thus taking the SS further to assume an active role within the distribution network. The product designed in thesis provides the DSOs with a remotely operated product but the way in which the network topology is designed the using automation techniques along with the panel is still in their hands and the product provides all the functionalities to achieve it.

6.3 Practical Implications

The research has analysed conceptions for understanding of the theoretically available techniques of distribution automation and the practically available compatible components which are now linked together through the study based on the network needs. It has provided an understanding as to how the Smart Grid concept for distribution automation can develop its need based implementation. The collection of primary data in the form of interviews and discussions from diverse organizations makes the outcomes of the research applicable to present and future practical needs. From the product point of view, it delivers practical capabilities from the basic monitoring to the full automated local or remote control for secondary substation. Being developed via detailed research through collaboration with university researchers, product manufacturers as well as network operators, it is practically designed, is customizable and is adaptable based on the network requirements and is thus future Smart Grid ready.

6.4 Research Limitations

Although the author has tried to be comprehensive with the research but as it is with all the studies, this has a few limitations as well, two to be precise.

Firstly, there is some limitation to the proposed algorithm for FLISR as the requisite for an NOP or a tie-switch for service restoration limits its application to networks in RMU configuration only. As this is not part of the designed product, this limitation can be ruled out. Secondly, as there is a blind spot between a switch and its CT, the IED cannot detect any fault there, although the chances of it happening there are extremely limited. But as both of these are outside the research scope, this this leads future scope for further studies. This could be explored for application in distribution networks in complex configuration such as a meshed or a multi-loop network where the restoration may as well be restrained by voltage regulation constraints. In addition, a cost-effective directionality feature could be explored without having to install fault detection devices on both sides of the switch.

6.5 Future Research

To the best of author's knowledge, the research represents one of the first attempts to find a customizable solution for solving current distribution network needs which are diverse while making it future ready for integrating it to the Smart Grid concept. This is in terms of the customizable design which has been also conceived with the ability to support supplementary functionalities which could be required in the future Smart Grid implementation. The designed product with its proposed solutions and their implementation is expected to have a strong impact on the development of standardized measurement systems and communication strategies for the reliable monitoring of the distribution networks.

Thus the research have taken a small step towards the implementation of automation and communication for the distribution networks as part of new SG functionalities and have paved path for further research in the future.

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APPENDIX 1: QUESTIONNAIRE - SECONDARY SUBSTATION MANUFACTURERS

What is the biggest need/challenge/improvement needed for the Puistomuuntamo (PM)? (From the electrical perspective)

1. Which is the most selling out of all the different PM models? (e.g. 2+1 or 3+1 or 5+1)
2. Is it feasible (technically/financially) to make the disconnector switch motor operated? (Using motor actuator keeping in mind the space needed and the price increase)
3. Do you have any budget (maximum amount) in mind for the product that can provide the remote control capabilities to the existing and future PMs? (As the whole price of the PM would increase)
4. Is there space (and how much) for a small panel as well as a motor actuator in the PM?
5. Is there any DC source (battery etc.) present in the PM?
6. Is there any antenna already used on the PM? If yes, can it be used for another signal as well? If not, is there a possibility to place one on the roof?
7. Is there a need for a local display with the automation panel (the control will be there as well as the switch for local/remote control)? From customers.
8. Is it possible/feasible (financially & practically/space-wise) to add circuit-breaker (vacuum/SF6 or any other) instead of the disconnector?

Mikähän suurin tarve/haaste/parannus tarvitaan Puistomuuntamo on? (Sähköisestä näkökulmasta)

1. Mikä on Teidän kaikkein myydyin malli puistomuuntamoista? (esim. 2+1 tai 3+1 tai 5+1)
2. Onko mahdollista käyttää moottoriohjattua erotinta kojeistossa? (Kun huomioidaan taloudellisuus sekä tilantarve)

3. Pystyttekö antamaan hinta-arviota Puistomuuntamosta, joka olisi varustettu etäkäyttömahdollisuudella?
4. Onko puistomuuntamon mahdollista lisätä kauko-ohjauspaneeli sekä moottorin toimilaite?
5. Onko Puistomuuntamoissanne käytetty akkua? Ohjauksiin yms.
6. Onko mahdollisuutta laittaa antenni puistomuuntamoon?
7. Onko asiakkaiden suunnalta tarvetta kauko-ohjaukseen?
8. Onko mahdollista käyttää katkaisijaa tyhjiö tai SF6?

APPENDIX 2: QUESTIONNAIRE - DISTRIBUTION SYSTEM OPERATORS

What are the biggest needs/challenges/improvements needed for the feeder distribution (outdoor)? (From the electrical perspective)

1. Which is the currently most implemented secondary Substation (SS) out of all the different configurations?
2. Which will be the most implemented secondary Substation (SS) out of all the different configurations in the future? (on pole or in Puistomuuntamo (PM))
3. Where are these located (near the city or in suburb) (as we need this information for analyse the need for the antenna for communication)?
4. Are there any problems you are facing with the existing equipment and are there any improvements that can be made to correct them?
5. Are you willing to upgrade the existing SS (PM or pole mounted transformers) by adding CBs in addition to reclosers/switch-disconnectors to existing SS for semi or full automation? (Are there any future plans for it?)
6. What are the future plans for new MV feeders as to the usage of underground cables instead of overhead conductors? (as a % of underground cables to the total feeders)

Mitkä ovat teidän suurimmat tarpeenne/haasteenne tulevaisuudessa 20kV jakeluverkossa?

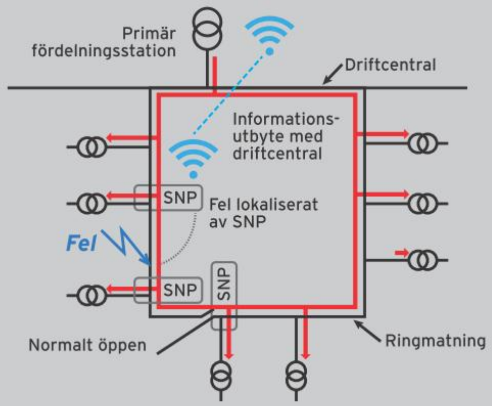
1. Millainen konfiguraatio on yleisimmin käytössä puistomuuntamoissanne?
2. Millainen tulee olemaan käytetyin puistomuuntamo tulevaisuudessa?
3. Millaisissa paikoissa nämä sijaitsevat, kaupungeissa vai haja-asutusalueilla?
4. Millaisia parannuksia haluisitte nykyisiin muuntamoihin verrattuna?
5. Aiotteko päivittää nykyisiä puistomuuntamoitanne tulevaisuudessa esim. kauko-ohjatuiksi?
6. Kuinka paljon aiotte tulevaisuudessa kaapeloida?

APPENDIX 3: TECHNICAL EVALUATION AND COMPARISON - IEDs

	ARC-TEQ	VIOLA	VAMP-Schneider	NETCONTROL	ABB
Model	*AQ E215*	*Arctic Control*	*VAMP 255*	*Netcon 100*	*REF 615*
General					
Real-time clock	?	Y	?	?	?
Processor	?	32 bit RISC	?	? (GW 102)	?
FLASH memory	?	8 MB	?	2 Slots	?
SDRAM memory	?	32 MB	?	?	?
Functioning Environment					
Temperature	-35 to +70 °C	-40 to +75 °C	-10 to +55 °C	-40 to +40 °C	-25 to +55 °C
Humidity	?	5 to 85% RH	0 to 90% RH	0 to 96% RH	0 to 93% RH
Power					
AC input	85 - 265 V	90 - 264 V	40 - 265 V	90 - 264 V	100 - 240 V
Frequency	?	?	50 - 60 Hz	45 - 65 Hz	50 - 60 Hz
DC input	85 - 265 V	85 - 200 V	48 - 220 V	24 V (3)	24 - 250 V
DC output	?	24 V	N	N	N (250 V AC/DC)
Consumption (w/o and with charging)	7 W/15 W	10 W/60 W	7 W/15 W	?	12W/18W DC 16W/21W AC
Communication					
Comm. Monitoring	N	Y	N	N	N
Auto-reconnection	N	Y	N	N	N
User Interface	Y	Y (Graphic)	Y	Y (Diagnostic web-based)	Y
Remote Configuration	Y	Y	Y	Y	Y
IEC 101	Y	Y	Y	Y	N
IEC 103	Y	N	Y	N	Y
IEC 104 for control commands	Y	Y	N	Y	N
Firewall	?	Y	?	Y	? (Encription)
VPN Tunnel	?	Y	?	Y	?
Network Interface					
Always ON comm.	Y	Y	Y	N	Y
Two-way comm.	Y	Y	Y	Y	Y
IEC 104 for SCADA	?	Y	?	Y	?
Ethernet	10 RJ 45	10/100 RJ 45 (with Isolation Transformer)	10 RJ 45	N	10 RJ 45
RS 232	Y	Y	Y	Y	?
RS 422	?	Y	N	N	?
RS 485	Y	Y	Y	N	?
Fiber Optic	Y	N	Y	N	Y
Protocol Conversion					
IEC 101 to IEC 104	N	Y	N	N	N
Modbus RTU to IEC 104	N	Y	N	N	N
Wireless					
GPRS	N	Y (max. 85.6 kbps)	N	Y	N
EDGE	N	Y (max. 236.8 kbps)	N	Y (3G)	N
GPS	N	N	N	Y	N
Radio	N	N	N	Y (Optional)	N
Antenna	N	Y (Stub/Detachable with cable)	N	Y (SMA)	N

	ARC-TEQ	VIOLA	VAMP-Schneider	NETCONTROL	ABB
Monitoring	(Many)		(Many)		(Many)
Temperature	? (7.6 module)	Y	N	N	N
Battery Alarm	? (7.6 module)	?	N	Y	N
Fault Detection and Localization	Y	N	Y	Y (GPS based)	Y
Disconnector					
Transaction time	N	Y	N	N	N
Energy	N	Y	N	N	N
Battery					
Testing	N	Y	N	N	N
Voltage	N	Limited time	N	?	N
Current	N	Limited time	N	?	N
Charging	N	Y	N	Y	N
Condition Monitoring	N	Y	N	Y	N
Battery Complete Discharge Alarm	N	Y	N	Y	N
Deep Discharge Protection	N	Y	N	N	N
Temperature	N	Y	N	Y (PT 100)	N
Indications (LED)	(Many)		(Many)		(Many)
Disconnector Status	Y	Y	Y	N	Y
Earthing Status	Y	Y	Y	N	Y
Status	Y	Y (Non-configurable)	Y	Y (20 configurable)	Y
Alarm	Y	Y (Non-configurable)	Y	Y (10 configurable)	Y
Reset Button	Y	N	Y	Y	Y
Control					
Local/Remote	Y	Y	?	Y	?
Space Heater	N	Y	N	N	N
I/O Interfaces					
Analog Inputs	5 I/4 U	2	5 I/3 U	12 (for CTs/VTs)	?
Analog Outputs	?	0	0	1 (250 VAC, 5A)	?
Digital Inputs	3 (Externally Wetted)	17	18	25 (modular)	?
Digital Outputs	4 NO + 1 NO/NC	0	0	0	?
Relay Outputs (Dry/Potential free contact)	5 (+)	10	9	8 (modular)	?
Safety					
L/R Switch	Y	?	?	Y (+ OFF)	Y (+ Station + Off)
Hit & Run	N	N	N	Y	N
Transformer Temperature Measurement	N	N	N	Y	N
Protection	(Many)		(Many)		(Many)
Motor Actuator Load current (Overcurrent & duration)	N	Y	N	N	N

APPENDIX 4: VEO SNP BROCHURE (SWEDISH VERSION)



VEO Smart Node Panel (SNP)

Smart Grid compatible 2.0

Bredd	300 mm
Höjd	400 mm
Djup	210 mm

VEOs SNP är framtiden inom sekundärstationsautomation. Tack vare SNPs flexibilitet kan den anpassas till varje kunds specifika önskemål. Med SNP får kunden totalkontroll även över sekundärfördelningar, såsom park- och stolptransformatorer. SNP kan användas i både nybyggda och redan befintliga stationer.Det primära syftet med SNP är att bygga upp en nod som kommunicerar med kundens driftcentral. Denna nod kan i realtid sända driftstörningsinformation till driftcentralen och vid behov vidta åtgärder.

Kommunikation direkt med kundens driftcentral och informationsutbyte med övriga SNP enheter, till exempel med GPRS, fiber, ethernet ellerliknande

Skydd av utrusting och nätverk i felsituationer

Övervakning av olika komponenter i nätverket, till exempel brytare, frånskiljare och transformatorer

Kontroll och manöver av brytare eller frånskiljare, lokalt eller via fjärrmanöver

Mätning exakta mätvärden för spänning, ström och andra parametrar nödvändiga för skydds- och kontrollutrustning