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FAULT LOCATION, ISOLATION AND NETWORK RESTORATION AS A SELF-HEALING FUNCTION

Master of Science thesis

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ABSTRACT

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One of the main emphasis of the smart grid is the interaction of power supply and power customer in order to provide a reliable supply of power as well as to improve the flexibility of the network. Along with this, the increased energy demand, coupled with strict regulations on the quality and reliability of supply intensifies the pressure on distribution network operators to maintain the integrity of the network in its faultless operation mode. Additionally, regardless of the huge investments already made in replacing aging infrastructure and translating "the old-fashioned grid" in a "Smart Grid" to minimize the probability for equipment failure, the chances of failure cannot be completely eliminated. In accordance, in the event of faults in the network, apart from the high penalty costs in which network operators may incur, certain safety factors must be taken into consideration for particular customers (for example, hospitals). In view of that, there is a necessity to minimize the impact on customers without supply and maintain outages times as brief as possible. Within this scenario comes the concept of self-healing grid as one of the key-technologies in the smart grid environment which is partly due to the rapid development of distribution automation. Self-healing refers to the capacity of the smart grid to restore efficiently and automatically power after an outage. Self-healing main goals comprise supply maximum load affected by the fault, take the shortest time period possible for restoration of the load, minimizing the number of switching operations and keeping the network capacity within its operating limits.

This research has explored insights into the smart grid in terms of the self-healing functionality within the distribution network with main emphasis on self-healing implementation types and its applicability. Initially a detailed review of the conception of the smart grid in order to integrate the self-healing and thus fault location, isolation and service restoration capabilities was conducted. This was complemented with a detailed discussion about the electricity distribution system automatic fault management in order to create a framework around which the aim of the research is based. Finally the self-healing problem coupled with current practical implementation cases was addressed with the objective of exploring the means of improvement and evolution in the automation level in the distribution network using Fault Location Isolation and Service Restoration (FLISR) applicability as a medium.

PREFACE

This study has been conducted and written by the author as thesis for M.Sc. Electrical Engineering with major in Smart Grids at Tampere University of Technology (TUT).

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Thanks a lot! Paljon kiitoksia! Muchas gracias!

2015

David Villarreal Sardina

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

ADA	Advanced Distribution Automation
ADMS	Advanced Distribution Management System
ALS	Automated Line Switching
AM	Automated Mapping
AMI	Advanced Metering Infrastructure
AMR	Automated Meter Reading
ASR	Automated Sectionalizing and Restoration
CA	Customer Automation
CAIDI	Customer Average Interruption Duration Index
CB	Circuit Breaker
CC	Central Controller
C-FDIR	Centralized FDIR Systems
CI	Customer Interruption
CIS	Customer Information System
CML	Customer Minutes Lost
CMI	Customer Minutes of Interruption
CT	Current Transformer
DA	Distribution Automation
DC-FDIR	De-centralized FDIR Systems
DER	Distributed Energy Resources
DES	Distributed Energy Storage
D-FDIR	Distributed FDIR Systems
DG	Distribution Generation
DGA	Distribution Grid Area
DIS	Downstream Isolation Switch
DMS	Distributed Management System
DOE	Department of Energy
DR	Demand Response
DSE	Distribution State Estimator
DSM	Demand Side Management
DSO	Distribution System Operator
EM	Electric Mobility
EMS	Energy Management System
ESS	Energy Storage Systems
ES	Expert System
EV	Electric Vehicles
FA	Feeder Automation
FACTS	Flexible AC Transmission Systems
FCI	Fault Circuit Indicator
FDIR	Fault Detection, Isolation and Restoration
FLISR	Fault Location, Isolation and Service Restoration
FM	Facilities Management
FPI	Fault Passage Indicator
FTU	Feeder Terminal Unit
GIS	Geographic Information System
GOOSE	Generic Object Oriented Substation Event
GUI	Graphical User Interface

GPRS	General Packet Radio Service
HV	High Voltage
ICT	Information and Communication Technology
IDMS	Integrated Distribution Management System
IED	Intelligent Electronic Devices
IGSD	Institute for Governance & Sustainable Development
LBS	Load Break Source
LTC	Load Tap Changer
LV	Low Voltage
MAIFI	Momentary Average Interruption Frequency Index
MAS	Multi Agent Systems
MINLP	Mixed Integer Non-Linear Problem
MP	Mathematical Programming
MV	Medium Voltage
NCC	Network Control Center
NCS	Network Control System
NIS	Network Information System
NIST	National Institute of Standard and Technology
NOP	Normally Open Point
OMS	Outage Management System
PLC	Power Line Communication
PMU	Phasor Measurement Unit
RAS	Remedial Action Schemes
RCD	Remote Controlled Disconnector
RES	Renewable Energy Resources
REP	Retail Electric Providers
RMU	Ring Main Unit
RTU	Remote Terminal Unit
SA	Substation Automation
SAS	Substation Automation System
SAIDI	System Average Interruption Duration Index
SCADA	Supervisory Control and Data Acquisition
SD	Switched-Disconnector
SG	Smart Grid
SHG	Self-Healing Grid
SLD	Single Line Diagram
SS	Secondary Substation
SSC	Smart Substation Controller
SSW	Sectionalizing Switch
SPS	Special Protection Schemes
SWOTF	Switch On To Fault
TSW	Tie Switch
VPP	Virtual Power Plant
VT	Voltage Transformer
VVC	Voltage Var Control
VVO	Voltage/Var Optimization

1. INTRODUCTION

The demands on electric power distribution grids have changed substantially compared to the time when the present systems were put into practice. The unremitting growth of electric energy consumption as well as the upcoming large-integration of Distributed Energy Resources (DER), based on Renewable Energy Resources (RES), e.g. photovoltaic systems, wind generators, biomass, result in a gradually more complex electric network. The traditional electrical power and energy system consists of bulk generation, a high voltage transmission grid, a medium and low voltage distribution system as well as the costumer. Such large and complex, non-linear system are prone to cascading failures due to single fault in transmission and/or distribution lines. The functionality and readiness of the power and energy system is a pre-requisite for the social and economic welfare of today´s society [1]. For those reasons, future distribution grids dictate new requirements on fault tolerance and service availability: in case of partial system failure, the system should be able to achieve its appointed objectives to the greatest possible extent without human guidance. For example, in the process of isolation of a fault, keeping the non-effective area under power is crucial. The restoration problem is usually a combinatorial problem owning to many combinations of switching operations that scale exponentially with system size. Several methods as centralized techniques, e.g. mathematical programming, complex and non-linear optimization, genetic algorithms, particle filtering, heuristics, knowledge based systems, etc., decentralized or Multi-Agent Systems (MAS) technology have been proposed in the literature to solve this type of problem. These centralized approaches mostly incorporate a centralized architecture and therefore depend on a powerful central computing facility to handle huge amounts of data resulting in a potential single-point-of-failure [2]. The vision of a grid capable of dynamic optimization of grid performance, rapid response to disturbances and minimization of their impacts as well as fast recovery into a stable operation point with little or no human intervention, is shared by many working groups such as the IntelliGrid Initiative [3] and the European Smart Grids Technology Platform [4]. Consequently, distribution companies are required to invest in sophisticated network monitoring and control systems as well as to enhance processes used at present. One of the main goals of distribution companies is to reduce outage costs. This improves profitability and provides a better quality of electricity distribution. A decline in outage costs involves different fields, out of which automatic fault management systems covers one part. This ´smart` concept is replicated throughout the electrical network under the notion of ´Smart Grid` (SG).

1.1 Research and motivation

With the increased deployment of DER into the grid, it becomes complex to manage the network operations. Nonetheless, SG applications help to improve the capability of electricity producers and consumers. This radically changes the way the system and the network switching is controlled and implemented in case of faults. It demands 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 resolve the faults in the least possible time in the distribution system; similar to how is realized at the transmission level. Thus, improving the reliability of power systems is an essential goal. This goal can be accomplished by realizing on the most important features of the smart grids, which is its self-healing ability. The centralized operation of Fault location, Isolation and Service Restoration (FLISR) function which is performed manually by human operators will be converted to automated FLISR or self-healing function. As a result, a system subjected to a fault will be able to automatically and intelligently perform corrective actions to restore itself to the best possible state in order to perform the basic functions without violating any constrains.

This automation is necessary in the network and has become the motivation of the thesis and thus the matter to research about. Given a power distribution network in a faulty state, the self-healing problem consists in finding the sequence of switching operation to reach the optimal operation state. In the case of smart grids, the complexity of smart grids as well as the complexity of power restoration increases because search space in presence of distributed generation, energy storage and mobile loads (electric vehicle) varies at each outage. However, observability of the smart grid network increases with the deployment of smart meters, Intelligent Electronic Devices (IEDs) in primary and secondary substations and remote operable devices.

The thesis mainly consists on a literature study about the smart grid in terms of the self-healing functionality of the smart grids. In chapter two the central idea of self-healing utilized in smart grids is introduced. This was complemented with chapter three, where a detailed discussion about the electricity distribution system automatic fault management was conducted in order to create a framework around which the aim of the research is based. In the fourth chapter, the major principles and all the relevant areas concerning fault location, isolation and system restoration as a framework of the self-healing grid is introduced. An extensive review of the existing self-healing architectures and its applicability via FLISR algorithms is developed in this chapter. In chapter five, numerous case studies were referred among which a total of five were briefed to understand the context and the environment in which FLISR systems function as well as to bring together any lessons learnt from recent projects and the effect they had.

1.2 Research methodology and materials

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 focus of the research was desk-based study in which 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. This included books and latest articles from sources including but not limited to IEEE and others.

The proposed qualitative data collection in form of the present thesis followed a continuous process. After a gathering of sufficient amount of information in form of numerous books, articles and journal on the various issues on automation for the distribution network, a deep analysis of such was accomplished. In some cases analysis of the reports and publication for a better understanding was required. Once the ideas were defined and clear, a categorization into segments of all the information was carried out. This resulted in a preliminary framework with findings for the study, which made it easier to start the execution.

2. INTRODUCTION TO SMART GRIDS AND SELF-HEALING

Nowadays, there is a need to enable the electric utility systems for operating the power system more effectively and efficiently aiming to enhance reliability, efficiency, power quality and utilization of distribution assets. On the other hand, it is also necessary to provide information for enabling the customer to make informed decisions about energy consumption patterns and behavior. SG can be defined as a power system which makes use of the latest technological advancements for accomplishing these two major goals [5].

The increased energy demand, in conjunction with strict regulations on the quality and reliability of supply, intensifies the pressure on distribution network operators to maintain grid networks in a faultless operation mode. In addition to the high penalty costs paid by the network operators in the event of power outage, there are also safety factors to be taken into consideration for particular customers (for example, hospitals). The possibility of a failure cannot be completely eliminated, and therefore it is needed to minimize the impact on customers as much as possible and keep outage times as few and as brief as possible. The importance to localize the faulty section of the distribution grid as fast as possible comes from this fact, so that normal operation can be continued quickly.

Traditionally, electric utilities utilized the trouble call system to detect power outages. When a fault occurred and customers experienced power outages, they called and reported the power outage. Then, the distribution system control center was responsible to dispatch a maintenance crew to the field. After the crew investigated the fault location, switching scheme(s) were implemented to perform fault isolation and power restoration operations. This traditional procedure for power restoration could take several hours to be completed, depending on how quick customers reported the power outage and the maintenance crew was able to locate the fault point and carry out the power restoration process. Recently, utilities have deployed feeder switching devices (reclosers, circuit breakers, and so on) with IEDs for protection and control applications. The automated capabilities of IEDs, such as measurement, monitoring, control, and communications functions, make it practical to implement automated fault identification, isolation, and power restoration.

2.1 Conception of smart grid

Recently, the term ´Smart Grid` has been used by governments, industries and research institutes. Smart grid is the new face of technology in the domain of electrical engineering. It refers to an upgraded electric power system that enhances grid reliability and efficiency by automatically anticipating and responding to system disturbances [6]. Smart grid itself is a broad idea. The whole concept does not refer only to the new trend in the energy sector to modernize the transmission or communication network. The idea of modernizing the electricity network equally comprises the integration of renewable energy and distributed generation sources, enabling the ability of reducing the power consumption at the end user´s load during peak times on demand (Demand Side Management), introducing grid energy storage for distributed energy and eliminating failures such as power grid cascading failures. The European Technology Platform proposes the following definition for Smart Grid- "A Smart Grid is an electricity network that can intelligently integrate the action of all users connected to it- generators, consumers and those that do both- in order to efficiently deliver sustainable, economic and secure electricity supplies" [7].

Continuous advancement in technology requires an enhancement in the traditional power grid [8]. Electricity has a tremendous importance in our daily life and economic development. Smart grid is the promising option for solving the power defects occurring today like blackouts, outages, overload, and transformer blowing up. In the same way, with the use of smart grids the improvement on efficiency patterns of electricity transmission and distribution can be achieved. The need to move onto an economically feasible and efficient grid technology can be put forward throughout the infrastructure of the smart grids [9].

As mentioned, with the advancement in Information and Communication Technology (ICT) and the expansion of the latest sensor technology, the field of automation has 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 [10]. SG, as referred above, has to do with an enhanced operational monitoring, control, intelligence, and connectivity via the utilization of advanced communication, electronic control and information technology [11]. Thus the concept of automation is extended to every level of the system counting 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 Distribution Generation (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 needed since the change towards the increase use of RES, which have a difficult-to-predict or "intermittent" generation pattern, is inevitable.

From the consumption point of view, SG provides the supplies for flexibility in demand thus supporting the Demand Response (DR) feature which is a part of the Demand Side Management (DSM). In view of that, more adaptability of the demand is introduced with the generation and the consumers taking benefits (financially) from it, while contributing towards an improved and efficient use of production resources and reduction in price fluctuations [12]. Electric Vehicles (EV), plug-in or hybrid, receive great attention in the SG concept as their use grows. Likewise, the potential of DR will improve as these can potentially be employed as controlled energy reserves when necessary and thus reducing the need for Energy Storage Systems (ESS) in the network [12].

From the network point of view, SG is fundamentally a concept of a fully automated power network which supplies 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. It is often discussed as a feature for remote monitoring and supervision of critical parts of the network via sensors and remote control of switches and breakers via functionality for communication. These solutions have been incorporated on the network for a long time, usually on the High Voltage (HV) level transmission networks and in generation plans. However, the Medium Voltage (MV) level distribution network, which is more widespread, has been left out [13].

From the technological perspective point of view, IEEE describes SG as the next-generation electrical power system that is characterized by the increased use of ICT at all the levels: generation, delivery and consumption of electrical energy [14]. Mohagheghi et al. define SG in a similar manner from technological viewpoint as a power system that includes the state of the art in ICT in order to reach improved operational monitoring, control intelligence and connectivity [15].

Although the scope of definition for the notion 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.

2.2 Smart grid objectives

Modernizing today´s grid will require a unified effort for a transition in which the SG vision will focus on meeting the following objectives [16]:

1. ***The grid must be reliable****:* power is provided when and where its users need it and with the required quality they value. It withstands disturbances without failing and correction actions are taken before users are affected
2. ***The grid must be secure*****:** a secure grid can cope with physical and cyber-attacks without suffering considerable blackouts or excessive recovery costs
3. ***The grid must be economic:*** it operates under the basic laws of supply and demand, resulting in fair prices and suitable supplies
4. ***The grid must be efficient:*** investments on cost control, reduced transmission and distribution electrical losses will lead to a more efficient power production and improved asset utilization. Furthermore, methods to control the power flow to reduce transmission congestion are used allowing access to low generating resources including renewables

5. ***The grid must be environmentally friendly:*** the aim is to reduce environmental impacts through initiatives in generation, transmission, distribution, storage and consumption. The usage of renewable energy sources has highly increased. Additionally, future design of the grid will take over less land reducing the physical impact on the landscape
6. ***The grid must be safer:*** a safe grid does not produce damage to the public or to the grid workers, plus it is sensitive to users who depend on it as a medical necessity.

2.2.1 Smart grid functions

The SG needs to perform the following functions in order to accomplish the above explained objectives [17]:

1. ***Accommodate a wide variety of DG and storage options***: the grid will incorporate a wide variety of generation and storage options. Renewable energy and distributed generation sources at mass scale is one of the most innovative aspects of a smarter grid. The increase in distributed generation will help to reduce the capital investment in generation and transmission
2. ***Demand Side Management (DSM):*** to motivate consumers to participate in the grid operation. Consumers are expected to actively participate in the electricity market and thus to play an active role in smart grids. This active participation will benefit the utility, customers, and environment to reduce the cost of delivered electricity. Customers will be able to decide on their consumption based on the electricity prize
3. ***Self-healing:*** this function may represent one of the vital functions of the SG, and the one on which this thesis will be centered. This is a new development and the extension of traditional relay technology and its ultimate goal is to provide users with always-ideal power, hence, improving system security and reliability as well as customer satisfaction. This will greatly allow to attain and enhance the above described objectives for smart grids
4. ***Resist attacks:*** the self-healing function of the smart grids will prevent the grid from both man-made and natural attacks. It will demonstrate resilence to attacks identifying the risk, isolating the affected area and finally restoring the unaffected parts
5. ***Optimize the assets:*** asset management and operation of the grid will be fine-tuned to deliver the required functionality at the minimum cost. Improved load factors and lower systems losses will be key aspects for optimization assets.

2.2.2 Smart grid technologies

The above explained SG functions must be equipped with several technologies. These technologies include [18]:

- Two way communication techniques to enable the participation of customers in order to achieve the necessary monitoring of the grid. Advanced Metering Infrastructure (AMI) is the automated architecture for two-way communication between a smart utility meter and a utility company. AMI provides the utility companies with real-time data about power consumption which allow customers to make their choices about energy usage based on the price at the time of use [9]
- Sensor and advanced metering technology such as smart meters, meter reading technology equipment, Phasor Measurement Units (PMU), and other measurements systems. These digital devices are used to obtain better reliability and asset management. Another important remark is that these meters will enable automatic DR by interfacing with smart appliances
- DA, which includes monitoring, control and communication functions
- Advanced power components such as advanced power electronic devices, storage devices, plug-in hybrid vehicles, smart houses, web services and grid computing
- Weather prediction, specially aimed for wind and solar power density
- Advanced distributed control. This provides the decentralized and on-line control of the grid components instead of the current central model.

The above features of the smart grid can be grouped in the following smart grid facets [5]:

- Smart generation: this includes the new tools that may be used for centralized generation facilities in the most efficient and economic manner incorporating the upcoming DG and DERs
- Smart transmission: PMUs and Flexible AC Transmission Systems (FACTs) for the precise control of the bulk power grid
- Smart distribution feeders: this involves new sensors that can greatly improve visibility of conditions on the electric distribution feeders (outside the substation boundary)
- Smart primary and secondary substations: including IEDs for optimal monitoring and control of primary and secondary equipment
- Smart metering: this involves advanced metering infrastructure that provides energy consumption information and energy pricing signals to the customer and support demand response functions.

These are complemented with upper level ICT functions including a variety of systems in the distribution network operation such the remote control system or the network information system which will be briefed in further chapters.

2.3 Smart grid for distribution network

As the topic of the thesis falls within the distribution network, the viewpoint of SG from this perception becomes important. Garcia et al. are of the belief that the essential components of distribution network will be automated with SG. This will enable a state diagnosis of the network leading to an improved management to the grid and a proficient integration of DERs in addition to enhancement in quality of service [19]. This automation aspect is very correct and is the most important. Mamo et al. also support this point and consider that with the improvement of contextual and technical progresses within the SG development strategy, the expectation from the automation of distribution network increases to grant innovative functions to the operators in order to enhance the network management [20].

With the rigorous constraints 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 complication to be handled in case of faults. The goal of SG can be fulfilled through the integration of intelligent micro grids which are small interconnected networks of DER systems (loads and resources) which can operate in an on or off grid mode [21]. This leads to the island operation mode of the distribution network which is a crucial function of the SG concept but its implementation is far quite complex. In line with this level of complexity lies another crucial feature of the SG as part of the distribution network. This is the ´self-healing` ability of the SG. As the main target of the research, this function is stringently described in the next segments. It is worth to note that this function conducts to the fully operation mode of the distribution network which is, as previously stated, an essential but complex function of the SG concept. This forms the base of this thesis research.

2.3.1 Distribution generation and smart grids

In order to drive smart grid developments and coordination efforts in the power industry, distributed generation has been identified as a crucial paradigm enabled by the smart grid deployments [22]. Distributed generation consists of decentralized generating units throughout the distribution network. In the context of smart grid, the incorporation of DG into the distribution network can give rise to two main benefits. First of all, it can enhance the reliability at each load point near the DG, which primarily benefit the users at these load points. In the second place, DG can defer the venture of investment due to the flexibility of its capacity and installation placement, which will benefit distribution companies. In addition, distributed generation offers power support when load increases during peak demand periods, which releases transmission and distribution capacity, thus reducing interruption that may turn into system outages.

A research carried out by the International Energy Agency [23] observed that a power system based on a large number of reliable small DGs is able to function with the same reliability and a lower capacity margin than a system of equally reliable large generators. However, implementing DGs in practice is not an easy task due to several reasons. Firstly, DG comprises large-scale deployments for generation from renewable resources, such as solar and wind that yield wide fluctuations in generation patterns. These generation patterns arising from these renewable resources and the electricity demand patterns are far from being equal [24]. Secondly, the authors of [23], [25] reported that the operation costs of distributed generators for producing one unit of electricity are high compared with that of traditional large-scale central power plants. Further, the introduction of DG units may endorse a number of technical issues to the system as well, such as thermal ration of equipment, reverse power flow capabilities of tap-changers, voltage rise, power losses, power quality (such as flickers and harmonics) or protection issues [26].

It is worth to note that the continuous development and deployment of DG has led to new concepts related to the distributed generation. Virtual Power Plant (VPP), for instance, refers to a large group of distributed generators with a total capacity comparable to that of a conventional power plant [24]. Such a VPP can even replace a conventional power plant while providing higher efficiency and flexibility. Nevertheless, a VPP is also a complex system requiring a complicated optimization, control, and secure communication methodology. Further explanations on VPPs can be found in [27], [28] and [29].

It is thought that distributed renewable energy will be greatly used in SG. In order to drive smart grid developments and coordination efforts in the power industry, distributed generation has been identified as one of the important areas for the smart grid developments [30]. However, multiple generation sources together with bi-directional power flow, power flow time coordination and management bring significant benefits and challenges for the existing power grids and microgrids. DG takes advantage of distributed energy resource (DER) systems (e.g. solar panels, wind turbines, etc.) in order to enhance the power quality and reliability.

In particular, the effect of DG on protection concepts and approaches (on which self-healing should be account for) needs to be understood and deserve special attention. Along with this, system reliability is another subject that should be embraced with the extensive use of DG within the SG. Reliably is the ability of an element or system to accomplish essential functions under stated conditions for a stated period of time [31]. System reliability has always been a major focus area for the design and operation of modern grids. Distributed generation (i.e. renewable resources), while complementing generation capability and adopting environmental concerns, aggravate reliability due to their volatility. While using some fluctuant and intermittent renewable may compromise the stability of the grid [32], [33], the authors of [34], [35] pointed out that innovative architectures and designs can offer great potential to connect DGs into the grid without compromising system reliability.

Chen *et al.* [34] proposed to take advantage of new architectures such as microgrid to make simpler the impact of DG on the grid. Intuitively, as loads are being supplied locally within a microgrid, less power flows within the entire grid infrastructure. Hence, the reliability and stability of the SG can be improved. A promising result was found from their research. When local power generation is introduced, even if the number of local generators is relatively small, the probability of cascading failures can be reduced drastically. Moslehi and Kumar [35] observed that an ideal mix of SG resources (e.g. distributed renewable resources, demand response, and storage) arises in a flatter net demand that eventually further increases reliability. Nonetheless, in order to realize this, a systematic approach in which a common vision for cohesive integration of these information technologies is necessary for expediting their deployment and facilitating the convergence of required standards. As a result, an architectural framework is proposed to function as a real representation of a common vision.

Distributed generation can cause many challenges in the existing protection of distribution networks as well. Since DG is generally connected at the distribution level, the introduction of new generation source can cause protection issues like false tripping of feeders, protection blind spots, decreased fault levels, undesired islanding, automatic reclosing block or unsynchonized reclosing [30]. Moreover, when a considerable amount of DG is connected to a MV network, the fault current seen by the feeder protection unit can be reduced, resulting in improper or non-operation of the relay or Intelligent Electronic Device (IED). This is called blinding of protection or under-reach of protection.

2.3.2 Demand response and its impact on smart grids

Traditionally, electric utilities have tried to match the supply to the demand of energy. However, this may result impractical and expensive, but also impossible in the longer run. This is because the total amount of power demand by the users usually involves a very extensive probability distribution, which necessitates spare generation plants in standby mode in order to respond to the quick changing power usage. In addition, the efforts to meet the demand could even fail, resulting in voltage drops, blackouts (i.e. electrical power outages), and even cascading failures. In SG, demand response controls the customer consumption of electricity in response to supply conditions. Demand response enables consumer load decrease in response to emergency and high-price conditions on the electricity grid. By using demand response, smart grids do no need to match the supply to the demand any more, but to balance the demand to the available supply. This is done by employing control technology or convincing consumers (such as through variable pricing), and hence attaining better capacity utilization.

DR is a relatively simple concept. Utilities incentivize electricity customers to diminish their consumption at critical, “peak” times, on demand. Contracts, made in advance, specifically determine both how and when the utility (or an acting third-party intermediary) allow to reduce the end user´s load. This is a win-win solution for utilities and customers. At times of peak energy demand, DR is a cheaper, faster, cleaner and more reliable solution than adding a peaking power plant [36].

In recent years, great attention has been dedicated to the role of demand response programs in enhancing the efficiency of the electric power industry. A considerable amount of project reports, research articles and books have been published on the subject mostly aiming on DR potentials and benefits [36-43]. From a customer ´s perspective, DR programs offer the possibility to manage its consumption and attain cost savings on electricity bills [37]. From the market point of view, DR is able to alleviate price spikes and volatility as well as to mitigate the potential of market powers and abuses [36]. From the network operator view, DR can decrease peak demand, thereby achieving operational and capital cost savings. In this sense, it will relieve the need to operate high-cost and high-emission generating units [38, 39]. It may also prevent, or at some point defer, the need for network reinforcement [40]. Besides, flexible loads supported by DR are ideal supplements to inherently variable energy resources such as wind and solar [41]. Finally, DR is able to shape load profiles to avert widespread blackouts at critical times when service reliability is threatened [42],[43]. A profound research on the topic of DR is provided in [44] where DR benefits and implementation challenges is discussed in detail. A review of the concept of DR, its benefits and costs as well as some real-world deployments is proposed in [45]. Last, in [35] the authors proposed energy storage devices as a valuable asset of demand response to accomplish a flatter demand profile; thus improving the system reliability.

2.4 Smart grids and self-healing grid

Smart grid is featured by reliable, self-healing, efficient, compatible and interactive characteristics, and it is the trend of modern power grid development, as it was explained before. Recent blackouts in North America, Europe, and other regions of the world accentuate the need to develop a smart power network with self-healing features that could respond to vulnerable operating conditions and prevent fatal outages. Self-healing is the key function for the reliable and high-quality power supply and one of the key research subjects of smart grid technology [46].

The concept of the Self-Healing Grid (SHG) was envisioned by the “Complex Interactive Networks/System Initiatives” launched by EPRI and United States Department of energy in 1999. Later on, “Intelligrid” of EPRI and “Modern Grid initiative” of United States Department of Energy take the self-healing as one of main research areas [46].

The self-healing functionality consists on instantly responding to system problems trying to avoid or mitigate power outages and power quality problems. This is achieved by continuously performing self-assessment to detect, analyze, respond to, and as needed to restore the grid components and network sections. The grid operates as an “immune system” in pursuance of grid reliability, security, affordability, power quality and efficiency. Thereupon, the self-healing function diminishes disruption of service, by means of modern technologies that can acquire data, execute decision-support algorithms, limit interruptions, dynamically control the flow of power, and restore service as fast as possible.

Self-healing main goals comprise supply maximum load affected by the fault, take the shortest time period possible for restoration of the load, minimizing the number of switching operations and keeping the network capacity within its operating limits [47]. However, some issues should be taken into consideration: voltage constraints, load classification, load shedding, number of switching operations, minimizing losses, sequence of switching operations, cables and lines loading and transformer capacity, etc.

Self-healing of power distribution systems is achieved via DA, specifically through smart protective and switching devices that minimize the number of interrupted customers during contingency conditions. This is accomplished by isolating faulted components and transferring customers to an optional source when their normal supply has been gone. Optional resources may incorporate neighbor feeders and DER such as Distributed Energy Storage (DES) [48, 49]. For this reason, some authors prefer to use the term ´self-restoration` instead of self-healing [50]. It should be mentioned that the implementation of self-healing in distribution systems needs to add schemes that are flexible enough to adapt to changing system loading as well as configuration conditions (including automatically modify protection settings) and operate distribution system components within their ratings which will be referred meticulously in further chapters.

As the key technology to ensure the grid stability and enhance the supply quality, self-healing has now become a hot research subject of smart grid. The research on self-healing can be divided into two areas, transmission grid and distribution grid.

2.4.1 Self-healing power transmission network

Transmission network transmits the power from large power plants to major load centers. This usually involves a meshed network fed with multiple power plants. As a consequence, the cutoff of one or several elements on the system will not affect the operation of the network. Therefore, the self-healing of transmission grid aims at continuously monitoring the condition of electric devices present in the transmission grid, detect, mitigate the apparatus´s problems and isolate the faulted device by fast protection. Other function for the self-healing at transmission level involve online security assessment, early warning and corrective control system stability to avoid cascaded blackout in the system [46].

At the transmission level, the self-healing smart grid intends to make use of available modern technologies with the aim of transforming the current grid to one with better capabilities for situational awareness and autonomous control against component failures. Thus, improvement in reliability and an increase in resilience can be achieved [51]. Various types of technologies have been adopted to provide today´s transmission network with self-healing features. Wide area monitoring and control has gained worldwide interest. This involves the collection of data and controlling a large region of the grid through the use of time synchronized phasor measurement units. Analyzing the ability of the smart grid to prevent wide-area blackouts and fast recovery from an emergency state is then possible. Also, detecting low voltage conditions and initiating corrections actions (e.g. load shed) [52].

The synchronize phasor measurements technology brings many potential applications and has become the measurement technique of choice for electric power systems. The phasor measurement units provide synchronized positive sequence voltage and current measurement within a microsecond as well as local frequency measurements and rate of change of frequency. This allows measuring harmonics, negative and zero sequence quantities and individual phase voltages and currents. Hence, phasor angle instability prediction, dynamic voltage stability monitoring and low-frequency oscillation monitoring are potential applications that can help deliver better real time tools that enhance system operators´ situational awareness.

Different from the Supervisory, Control and Data Acquisition (SCADA) system, system synchrophasor technology allows the collection, sharing and delivery of synchronized high speed, real time and time synchronized grid condition data across the entire system. Accordingly, this data can be utilized to allow grid operators to understand real time conditions and emerging grid problems in such a way that a wide area visibility is shaped. In this way, better diagnose implementation and evaluation of corrective actions to protect systems reliability is accomplished [52].

Special Protection Schemes (SPSs) and Remedial Action Schemes (RASs) have also been deployed and incorporated in power systems as self-healing control actions to prevent cascading failures. Last, another important control action for load self-healing control is load shedding [53].

2.4.2 Self-healing power distribution network

Distribution network directly faces customers, and any faults or disturbance on it will affect the supply quality, and thereupon the reliability and power quality. The self-healing purpose of smart distribution network is first to reduce outage due to momentary interruptions to improve system reliability. Secondly, the optimization of the power quality, with special focus on mitigation of voltage sag problems, and third avoid the system from the damage of external attacks and natural disasters.

At distribution level, DA technologies are being employed to enable the distribution system self-healing capabilities. The main functions of DA consist of real-time monitoring, control and automated operation of distribution feeder. An effective DA system will be capable of efficiently optimizing its operation, extending asset of life and improving its reliability in a number of zones [46]:

- Expediting fault detection, isolation and service restoration
- Improving power quality by remote voltage and power factor control
- Intelligently reconfiguring distribution network to reduce losses
- Increasing infrastructure reliability
- Reducing operating and maintenance costs
- Enhancing customer satisfaction.

As the scope to develop falls within the distribution network, it becomes pertinent to understand the distribution automation network scenario which is done in next segment.

3. ELECTRICITY DISTRIBUTION SYSTEM FAULT MANAGEMENT

Electricity distribution network control is currently dependent on computer based systems. Effective monitoring systems in addition to level and well implemented distribution automation systems are necessary for supply quality requirements. Fault management process can also be improved through effective control systems and data communications.

The electric distribution system consists of two main units: the primary process and the secondary process. The primary process contains both primary and distribution substations, as well as MV and LV networks according to the voltage level. This process contains the actuators in the network such as transformers, overhead lines, cables, switching devices, fuses, reactors and capacitors. The secondary process consists of systems and devices which are used to monitor and control the primary process. These secondary devices form an interface between the processes for communication and data transfer. These include the substation relay protection, the remote control system, and automation devices concerning to substations, network and customer consumption points. Examples of these devices are relays, instrument transformers, sensors, data transmission systems and information systems. These devices are generally called intelligent electronic devices (IEDs).

In addition, a third unit can be considered: the information system [54]. This system comprises a collection of distribution support systems depending upon the distribution company. Additionally, even the remote control system is associated to the secondary system, it can also be considered as part of the information system. Typically used information systems in distribution management are SCADA and Distributed Management System (DMS) [55].

Many other systems and applications used to assist the network operators can be found, but only the essential units are considered here.

3.1 Distribution automation

The rise in electrical power demand and the subsequent increase in network complexities require improved levels of automation and communication for remote control as well as for management of the power network [56], thus necessitating the upgrading of the existing network infrastructure. In this light, this necessity to enhance the distribution system operation performance and to boost the application of ICT, the notion for the automation of the distribution network, within the scope of SG, has been denoted to with numerous but yet similar names. The basic terminology used is ´distribution automation` with some authors referring to it as Advanced Distribution Automation (ADA). As an essential element of SG, DA facilitates the deployment of the advanced computer and communication technology and infrastructure to develop the management and operation of distribution network from semi-automated approach towards a fully automated one [11]. 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 [57]. Since then, DA has advanced and evolved into a recognized concept. Nowadays, with the availability of cost-effective ICT along with the industry-wide momentum towards SG, DA has been given renewed attention to produce more reliable and efficient distribution systems.

Although the understanding of DA varies widely, it refers to a blend of emerging technologies, such as switching technologies, sensor detectors, and communication protocols that are used to automatically control and monitor the operation of the distribution network [58]. DA also refers to the management, operation and supervision of the electricity distribution network. It generally covers functions for safety and protection as well as operation and control. Additionally, DA offers functions for business and asset management.

Automation for operations in the entire distribution system is referred to the DA concept. The subject of DA embraces all aspects of the distribution system including distribution planning, protection, design, reliability, economics, load management, Network Control System (NCS), generally called SCADA, etc. Essential systems in DA are NCS, Substation Automation (SA), Feeder Automation (FA) and Automatic Meter Reading (AMR) supported with DMS [59].

In order to perform these functions, control strategies, computer software, and a communication system are required features to perform these functions. At present, DA systems work in a centralized way, meaning that only one Central Controller (CC) reads all the data collected from the system through the remote monitoring, and then implements the associated control actions. Processing all data in a central place represents a drawback and limits the efficiency and reliability of DA operation. The reason for this is the vast amount of information that needs to be processed to decide the control actions. Additionally, a considerable amount of human intervention is needed during faults [60].

The DA benefits include but are not limited to financial benefits, operational and maintenance benefits, customer related benefits and others [61]. There are far too many benefits of DA and it would be impractical to describe them all. However, the reliability improvement as part of operational benefits may be considered the greatest priority as these days reliability is tightly connected to financial compensation for the network operators. The reliability measurement techniques will be described in following segments, as they are being referred throughout the whole work.

3.1.1 Categories of distribution automation

DA, with its wide-ranging capabilities and applications, can be implemented at different levels of the network [62]. Accordingly, there are diverse ways to classify the automation functions which are monitoring, control, measurement and protection. In terms of location, DA functions can be classified into three category levels [63, 64]:

1) ***Secondary Substation (SS) automation:*** the DA functionalities at the SS include:
    a. Substation equipment monitoring and control (load 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) ***Feeder Automation (FA):*** 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. Intentional (planned) islanding [5] for island operation of the network i.e. Microgrid Management (MM)
    d. FLISR. This is the aim for the thesis research.
    e. Optimal network reconfiguration for the optimal setting of switch orders and to calculate the load among the feeders lines which are redistributed [65].

3) ***Customer Automation (CA):*** the DA functionalities at the customer level are wide. These may include:
    a. Load control
    b. Real-time price signaling
    c. Remote meter reading and billing (Automatic Meter Reading)
    d. Automatic Connection and Disconnection
    e. DR and LM as part of DSM.

Apart from the above mentioned features, there are 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 some others which are typically located at the NCC.

From previous functions, the distribution feeder automation function will be the focus of the research work. This consist on the monitoring and control of devices located out on the feeders such as line reclosers, load break switches, sectionalizers, capacitor banks and liner regulators. Apart from Volt/Var Control (VVC), Automated Line Switching (ALS) is the main feeder automation application. ALS is proposed as a valuable asset for taking advantage of DERs and for optimal network reconfiguration so that peak loading and loses can be reduced via load balancing. The primary ALS application is Fault Location, Isolation, and Service Restoration (FLISR), which uses automated feeder switching to detect feeder faults, determine the fault location (between two switches), isolate the faulted section of the feeder (between two feeder switches) and restore service to "healthy" portions of the feeder. These functions come under the concept of automation for the distribution network within the SG which is briefly described in the next segment [47].

3.1.2 Fault management via distribution automation

The smart grid concept is driving the deployment of a series of self-restoration schemes in the form of DA applications. In line with this, the major goal of the DA system is fast and precise identification and handling of a fault in order to narrow fault coverage and shorten fault outage while enhancing the quality and reliability of power to customers [66]. 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 (FLISR). As the research focuses on this idea, it becomes necessary to briefly discuss the potential benefits of FLISR functionality within the distribution network which is done next.

Process:

In case of a fault scenario on the distribution network, the substation feeder protection trips and shuts down the power on the entire feeder. This results in disruption of service to all customers on that feeder (including industrial, hospitals, commercials and residential). A typical fault scenario and outage time comparison without FLISR implementation is demonstrated in *Figure 3-1*.

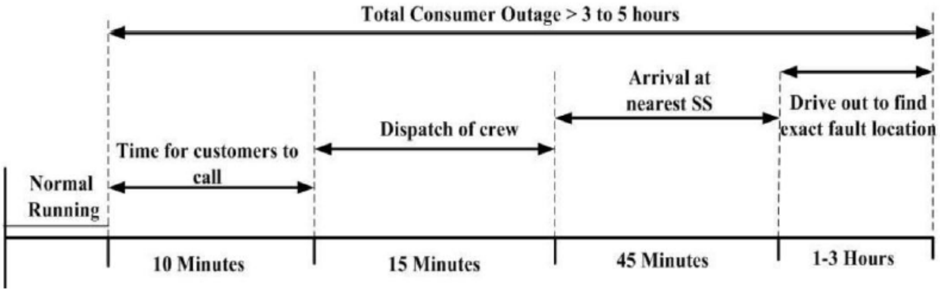

Figure 3-1: Fault management timescale (*without FLISR process) [67]

*The time frames are estimated for analysis purposes and depend very much on the network characteristics

It can be observed from the figure that the full fault management process takes approximately 3-4 hours per outage. The process works in such a way that when the faulty feeder has been tripped, the faulty section on the tripped feeder, that 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 is not automated in any form and thus communication with the NCC is not possible, the remote monitoring of faults as well as control in not possible either. This results in long supply interruptions; thereby hindering the reliability and security of supply. Once the fault location is tracked, manual fault isolation from both sides needs to be fulfilled using switches. Finally, the fault is repaired and the supply is restored. Note that the supply could also be restored earlier if a backup connection is available for that part of the network.

On the contrary, when this process is automated, often referred to as the FLISR process, the total outage time can be cut down to approximately 1 hour per outage or less as shown in *Figure 3-2*. Nevertheless, the outage duration also depends on some other factors including but not limited to: number remotely controlled switches, number of manual switching operations, number of backup connections, capacity of backup connections, manual switching operations and others.

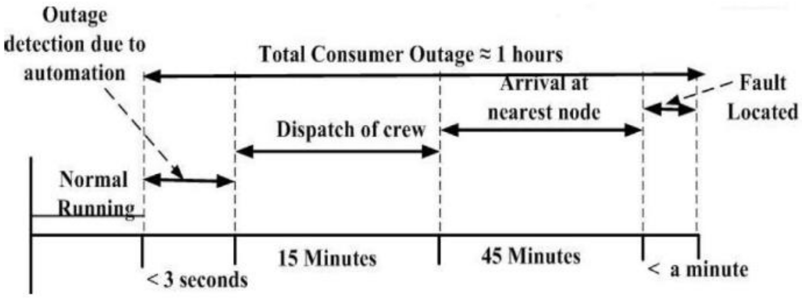

Figure 3-2: Fault management timescale (*with FLISR process) [67]

*The time frames are estimated and depend very much on the network characteristics

The fault management process in this case is similar as stated previously, but the manual operation is performed remotely (mostly) using monitoring, protection, control and communication equipment. In case manual switching operations (human intervention) or any agent external to the system and thus human intervention is necessitated, these can be denoted as assisted or partially automated FLISR systems. The number of controllable switches (Circuit Breakers or Switched-Disconnectors) is agreed by the Distribution System Operator (DSO) upon the number of faults and other factors.

Another example of the time frame is illustrated in *Figure 3-3* below, where it can be appreciated the time frame needed to perform the fault location, isolation of faulty segment and restoration of power to healthy segments when automation takes place. From the figure it can be observed that with automated FLISR actions, the fault can be located within a range of 15 seconds, isolate the faulty section within 45 seconds and re-energize power in less than a minute.

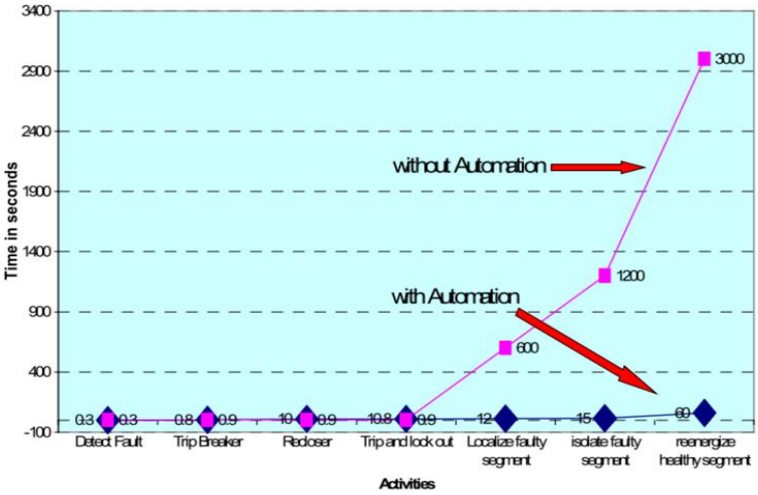

Figure 3-3: Influence of automation on outage time [68]

In short, when conventional operation (without FLISR) is used, there is a need for studying the specific fault location and executing manual switching to isolate the faulted area and restore service to customers located on healthy feeder sections. In this case, customer trouble calls may play an important role, and human intervention, either for fault location or switching operations to restore service, is vital. FLISR on the other side enables detect faults and restoring affected customers faster and with limited human intervention. When FLISR is used, power is rapidly restored to customers located on healthy units of a feeder. Likewise, if FLISR switching and protective devices are monitored in real-time then there is no need to wait for customer trouble calls to dispatch crews. Hence, it seems obvious that reliability benefits of FLISR can be seen on reducing operators and crews´ workload, which at the same time increases efficiency and reduces operation costs.

Uluski et al. have categorized the benefits of utilizing FLISR process as [69]:
a) Functional benefits:

- Reliability improvement of SAIDI, SAIFI, and other reliability statistics
- Reduce “energy not supplied” (kWh)
- Provide “premium quality” service
- Reduce fault investigation time.

b) Monetary benefits:

- Increase revenue (sell more energy)
- Reduce customer cost of outage
- Additional revenue from “premium quality” customers
- Labor/vehicle savings
- Achieve regulatory incentives (when available).

For integration in the SG concept, Sahin et al. have proposed a DA system that is capable of performing FLISR process in distribution systems which incorporate DG and interconnected feeders [70]. Many other researchers have addressed and proposed several other schemes. In this light, there is an ongoing trend in the industry for applying a series of self-restoration or self-healing schemes in the form of DA applications. This is due to several facts such as the incentives provided through government-funded programs [71], the development of DA technologies and the availability of a variety of communication technologies that facilitate its implementation.

3.1.3 Reliability measurements

There have been plentiful mentions about the benefit of DA and SG for enhancing the reliability of the supply but the question that comes along is how this can be measured. Evaluation based on statistics or based on calculations (reliability analysis) is one option. The statistics are useful in monitoring of real performance and the effect of reliability improvement investments whereas the calculation is useful in analyzing and comparing the outcome of alternative reliability improvement methods. The basic categorization is based on the following criteria [72]:

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 fulfilling 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 include:

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

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

where U_i is the annual outage time

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

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

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

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

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

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

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

These are mostly annual indices with some others also employed based on different parameters such as Customer Minutes Lost per average 100 customers (CML) or Customer Interruptions per average 100 customer (CI) among others. Based upon many regulatory standard guidelines, many distribution utilities are measured based on power supply reliability indices to evaluate qualitatively how well and effective they are delivering power to their customers. Besides, distribution utilities may be subjected to regulatory penalties if the reliability performance is not accomplished following the proper guidelines. With the primary goal of the distribution system being reliable supply and quality power, the reliability indices of SAIDI, SAIDI and CAIDI offer relevant performance measurements [73]. When the reliability of power supply is necessitated at higher levels, DA becomes obligatory for improving these distribution system indices [74]. From the DA benefit point of view, research done by Simard & Chartrand has found out that for enhancing 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: rising network robustness or division of feeder to decrease the number of customers per section [66].

3.2 Systems in distribution network operation

Distribution network operation means daily switching and control operations of the distribution network. The objective of the network operation is to provide high-quality electricity safely and minimize the total costs related to the network. Main functions of the distribution network operation include switching state monitoring, topology and fault management as well as switching planning. Distribution network is remotely operated from the DSO´s NCC; hence information systems as well as data transfer and communication play an essential role on the operation process. The most common information systems employed in NCC are SCADA and DMS systems and they are used to ease and support the operations. Substation automation and feeder automation are lifeblood for network operation process. Automation functionalities and remote control system permit network monitoring as well as remote control from the NCC. Also, LV network automation is practically limited to the AMR meter functionalities such as remote meter reading, load shedding and fault indication.

3.2.1 Remote control system

The remote control system incorporates the control center system, better known as the SCADA system. It also contains data communications and Remote Terminal Units (RTUs) in substations and network [75]. The remote control system is used for centralized control and monitoring of distribution network facilities, such as substation relays or Remote Controlled Disconnectors (RCD). These are communicated with the SCADA system through data processing facilities. Data can be transmitted from SCADA to RTU (for example through breaker control or relay configuration) as well as from RTU to SCADA (for example current and voltage measurements, status indication and alarms).

The SCADA system consists of an information system which is used for real-time monitoring and control of the distribution network. More precisely SCADA acquires data from various sources, pre-processes and stores it to a database accessible to different users and information systems. It has a user interface for the operators in the control center which allows it to perform the remote controlled of the switching components of the network. Furthermore, SCADA systems typically provide tools for remote relay configurations and also for power quality monitoring and optimization [55].

SCADA is used in DSO´s NCC and enables real-time process data from the network like alarms, status indications, current and voltage measurements, fault information and event data. It comprises a number of computers, application programs, database and Graphical User Interface (GUI) as well as connections to the other information systems, such as the DMS.

3.2.2 Network information system

Network Information System (NIS) is the most important tool in distribution network planning. NIS is also known as Automated Mapping, Facilities Management and Geographic Information System (AM/FM/GIS) and its main functionalities involve network planning and analysis as well as information management. This network database system includes information about network components (e.g. conductors, switches, breakers, distribution substations and protection). Also information about location, technical details of the components, maintenance or geographical information is contained within NIS. It is worthwhile to mention that NIS is also used in configuration management, calculation for voltage drop and power losses, network planning, statistics, and reporting.

3.2.3 Distribution management system

The DMS, also known as Energy Management System (EMS), is an intelligent decision support system for distribution network operation and management. DMS combines into a single system the SCADA process data, the NIS data, and nowadays also AMR data.

The main idea of the DMS is that of being part of an integrated environment composed of distribution automation (e.g. protection relays), the SCADA, the automated mapping, facilities management and geographic information system, the customer database, and a telephone answering machine. The DMS utilizes AM/FM/GIS database to create a static model of the distribution network. AM/FM/GIS database contains the detailed data of network components and network nodes. The customer database, known as customer information system (CIS) is utilized to contain customers ´energy consumption data` [75]. The applications of the DMS may be categorized as follows: network state monitoring, operations planning and fault management. *Figure 3-4* illustrates a classification of the main set of functions of the present entity.

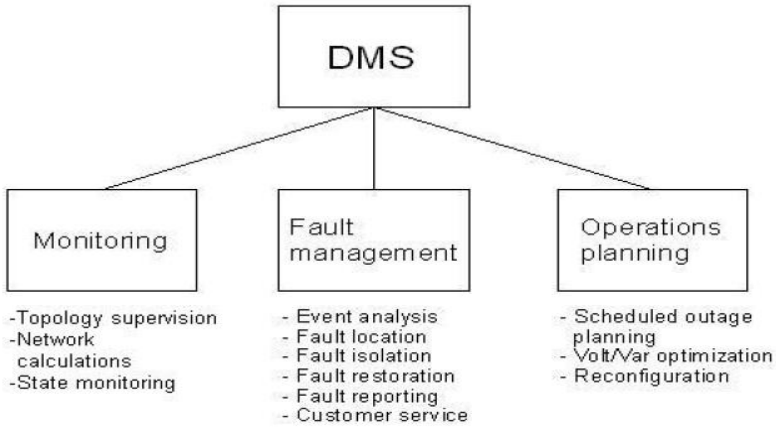

Figure 3-4: Functions of a distribution management system [55]

The main objective of the DMS is to minimize the operational costs (e.g. power losses, outage costs) owing to the technical constrains (e.g. voltage level, thermal limits, operation of protection). The DMS presents the real-time electrical state of the distribution network and proposes necessary actions for abnormalities that may occur (e.g. faults, voltage drops, overloadings). It also includes many advanced functions useful for the control center operator in network operation. These applications range from maintaining of the switching state through the graphical user-interface, real-time network monitoring and optimization based on sophisticated network calculations to short term load forecasting, switching planning, and fault management. The DMS operation is based on interactiveness. The operator is the one responsible for the ultimate decision making as well as for accomplishing the switching orders or other required actions (e.g. changing of the protection relay settings). Nowadays the DMS has also a duty of automatic switching in a fault situation, which will be discussed in the upcoming segment.

3.3 Distribution network configuration

A three phase circuit coming out of the substation is known as a feeder [76] and there are plentiful ways in which these feeders can be configured in a distribution network. Primarily, distribution networks, both primary (MV) and secondary (LV) are planned as radial networks as they offer many advantages comprising [76]:

- 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 contain normally open tie points for reliability improvement which provides with ring formation capabilities to the network. This comes under the concept of Ring Mains Units (RMU) as shown in *Figure 3-5* below:

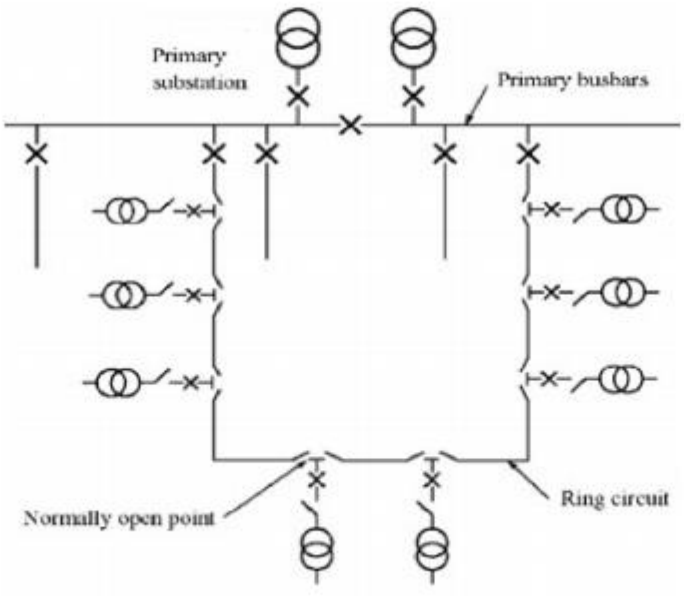

Figure 3-5: MV network in ring main unit configuration

This has the prerequisite of the RMU unit as the basic component as shown in *Figure 3-6* below:

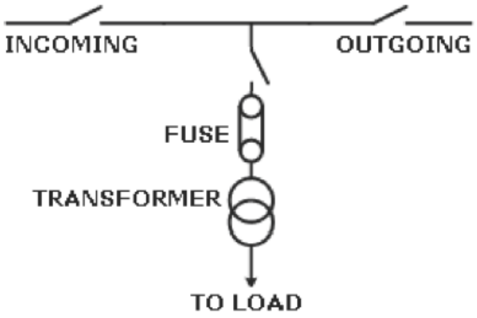

Figure 3-6: Basic RMU unit for secondary substation

Many primary distribution systems are designed and constructed as meshed networks, but on the other hand are operated as radial feeder systems with normally-open tie switches due to simpler switching and protection equipment in radial configuration but at the cost of reduced reliability. These tie switches can easily transfer unfaulted, out-of-service load to neighboring feeders to decrease the total load that has to be cut off over a prolonged period after a fault. 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 can be operated manually or remotely or automated switches or reclosers can be used for automatic operations. When a fault occurs in an electrical distribution system, the unfaulted de-energized areas have to be supplied with power as soon as possible so to ensure minimal reduction of system reliability. Though repairing the fault may take a few minutes, it is possible to quickly restore power to areas interrupted due to the fault or the resultant protections tripping if they can be temporarily connected to neighboring feeders carrying the extra load.

3.4 Automatic fault management as a DMS application

Fault management is one of the most important tasks and requires immediate actions from the operator for both business and safety reasons. The purpose of fault management is to provide permanent and steady electricity distribution to the customers and to minimize the expenses of the fault appeared. An automated fault management system automatically or semi-automatically performs fault isolation and supply restoration for a faulted feeder. The potential functionality of automation in fault management aims on reducing outage costs of customers and avoiding unneeded switching operations in the distribution network.

Several components must be put in the distribution network in order for the deployment of the automated fault management systems to be effective. First fault indicators are used to detect the existence of a fault by measuring voltages and currents on the feeder lines in order to notice an abnormal situation. Then remotely controlled switches (automatic switches) are employed to open or close line feeders to complete the fault isolation and power restoration process. In order to remotely monitor the status and control the previous components, communication nodes embedded with their protocols are needed to enable substations to communicate with each other [77]. The automatic switches are also controlled remotely using messages exchanged over the communication network based on fault indicator measurements which are also sent over the communication network.

3.4.1 Fault management process

Fault management is the process of detecting faults, identifying faulty lines or sections, and then isolating the faulty parts. Service may be restored by using the healthy parts of the network. In non-automated systems, switching actions are implemented by maintenance crew in order to restore electric power. For the present dense distribution networks, non-automated fault management costs money, time and manpower in order to repair the fault situations [78-80]. As a result, the latest trend is to apply automated fault management techniques to improve the quality of service and reduce the mentioned disadvantages of manual fault management. Automated fault management systems are a necessary part of future smart grid operation. A successful fault management process can be categorized by the four essential steps [79-83]:

1. Detect fault occurrence reliably and quickly
2. Locate the faulty section quickly
3. Isolate the faulty section
4. Restore the power to the healthy part of the network.

A comprehensive fault management system should have then the capability to detect different types of fault such as permanent and transient faults.

The critical issue in the fault management process is the detection of the fault. In case of short circuit faults or earth faults, the protection is based on tripping and the fault is detected when the circuit breaker is opened. This is the starting event of the fault management process. However, in networks with continued earth fault operation the protection is an alarm event, which is obtained from the relay protection. Nevertheless, this is not a highly reliable indication and major importance has been given to the correct fault section location by Fault Passage Indicators (FPIs) [84].

The automatic fault management process can be divided into two functional levels, which depend on the equipment at the secondary substation. The higher level relies on full automation and the switches in the network are remote controlled. Automatic fault management must comprise of a reliable fault indication. Consequently, local measurements are used. In practice, this means that both currents and zero sequence voltages at the secondary substations are measured. In case of short circuit faults, the fault is detected by means of current amplitude measurement and overcurrent relay principle. For single phase to ground faults, the directional relay principle is employed to measure the zero sequence voltage and sum current, and thus comparison of their phase angle can be used to detect the fault. This is a proven solution and seems to be reliable enough to be used as a basis for full automatic switching actions [85].

The applicability of this full automation depends highly on the costs of implementation versus the benefits obtained. Both depend very much on the circumstances to be considered, on the secondary substation, the costs associated to retrofitting, the load criticality benefits and on the expected fault density of the adjacent network. Siirto et al. states that a reliable fault indication is the lower level core of the fault management; whereas full distribution automation is the higher level core of the fault management [85]. The need of fault indicators to enhance the utilization of full DA is also discussed in [86].

The following sequence diagram in *Figure 3-7* illustrates the necessary interaction between the relevant actors in the automatic fault management.

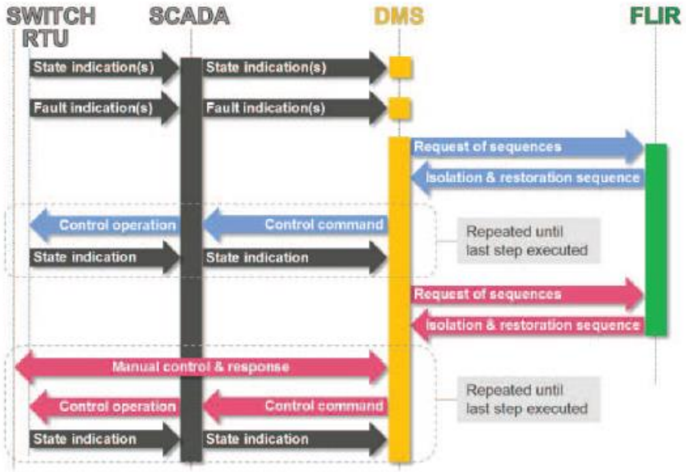

Figure 3-7: Interoperability sequence diagram [85]

The automatic fault management process can be described for the case of short circuit faults following the next sequence of steps:

1. The circuit breaker is opened due to overcurrent relay tripping. The existence of a fault and a faulty feeder are then identified
2. The network topology is analyzed by the DMS. DMS provides the network connectivity at the time of the fault and the topological hierarchy of the secondary substations
3. DMS collects the information from the fully automated secondary substations. The fault indication is based on local measurements and simply involves 0/1 signal in order to indicate whether the fault current was detected or not
4. Next is the analysis of the fault indicator data. The active fault indications are followed until the line section where fault occurred
5. The switching sequence is now created to isolate the faulty line section and restore the supply in the main feed direction
6. The topology needs to be analyzed again to check whether there is an automated line section behind the faulty line section that could be restored using a backup feeder supply. If such line section is found, then the corresponding switching sequence is added to the sequence created in the previous step
7. The next step is the submission by the DMS of the switching sequence to the SCADA system to be implemented in practice

8. Once automatic switching is successfully processed, DMS analyses the network topology to check whether line sections remain under outage. If that happens, the lower level automation stars and fault indicator data (e.g. current measurements) are collected
9. One of the last steps is to compare the fault indicator current measurements and displaying the fault indication result on the network diagram. This is fulfilled by the DMS
10. Lastly, the faulty section can be isolated by a combination of manual and remote controlled switches, and the rest of the other line sections can now be re-energized.

Combining support solutions for the fault management comprises of real time network information, network modeling, topology information, fault management solutions and distribution automation. Network information is managed using information systems, e.g. NIS. However, utilities use SCADA for network control and for acquiring network status information. Modern advanced DMS includes network information and real time information as well as applications to support and enhance network information. FLISR solutions offer great potential for automation of the manual fault restoration procedure. FLISR can be seen as a new control-center-based automation system deploying advanced technology on the network to remotely monitor the high and low voltage networks (urban distribution networks or rural networks). In following chapters, different technologies are explained to support utilities achievement of fully automated ways for controlling and monitoring the distribution power network.

4. FAULT LOCATION, ISOLATION AND SERVICE RESTORATION (FLISR) AS A SELF-HEALING FUNCTIONALITY

The idea of narrowing the outage time in case of a fault on a distribution feeder is not new. For instance the application of a recloser is an example of an original Self-Healing Grid (SHG). This principle especially works in cases where the vast majority of faults on a distribution feeder are temporary. The recloser interrupts the fault current by cutting off the faulted section of the distribution feeder, enabling the arc to extinguish. After a short period of time, the recloser re-energize the distribution feeder back again and when the fault is removed the feeder remains in service. Otherwise, after several attempts, the feeder will be shut down permanently. An example of the latest recloser advancement is given in [87, 88]. More developed techniques, such as DA, can be applied to create a self-healing grid which can govern permanent faults too.

A self-healing grid will be established by means of distribution automation applied to some secondary (and/or primary) substations together with a SHG algorithm (also referred as FLISR algorithm). This can be implemented at different levels within the operation network such as control center (centrallized intelligence), primary substation or distributed among the secondary substations (distributed intelligence). According to this levels of location of the SHG algorithm, self-healing or FLISR architectures are implemented. A full description for all of them will be elaborated in the forthcoming points.

Self-healing is a key feature and has high significance in the operation of the smart grid. Self-healing distribution systems have two functions [89]: self-prevention and self-recovery. Self-prevention refers to real-time performance evaluation and continuous optimization during normal operating conditions. Self-recovery refers to automatic fault detection, isolation and supply restoration (FLISR) during disturbances or fault conditions. This manages the faults automatically without human intervention in an order as follows: detection of the fault through sensors and monitors (fault location), location of the switches on both ends of the fault, isolation of the location at which the fault happened by opening the switches located earlier (isolation), and reconfiguration of the network to connect the loads with backup power resources (service restoration). Conversely, assisted healing systems denote those processes that necessitate for partial manual operations or some kind of human intervention. Thereupon, Fault Detection, Isolation and Restoration (FDIR), better known as Fault Location, Isolation, and Service Restoration (FLISR) [90] can be viewed as one of the functions within the self-healing technologies of the smart grid which is achieved via distribution automation [91, 92].

FLISR includes automatic sectionalizing and restoration, as well as automatic circuit reconfiguration [93]. These applications involve DA operations by coordinating operation of field devices, software, and effective communication networks to automatically determine the location of a fault. FLISR enables a rapid reconfiguration of the electricity flow so that customers avoid long outages. Additionally, FLISR operations rely on rerouting power and they usually require feeder configurations that contain multiple paths to single or multiple substations. This provokes redundancies in power supply for customers located downstream or upstream of a downed power line, fault, or other grid disturbance as well as an advanced communication infrastructure. Broadly, in addition to an advanced communication infrastructure, two technology elements are required to provide FLISR capabilities. These are field devices and algorithms. Field devices comprise sensors and switches. Sensors are responsible for detecting issues occurring on the network, while switches are used to control the power flow inside the network. Likewise, algorithms consist of the mathematical logic which monitors switching activities when isolating equipment on the network. In the upcoming sections more detailed information about the FLISR process flow, FLISR schemes and its applicability as well as real case scenarios will be addressed.

4.1 Process description

The fault management in the FLISR process is divided into four parts: fault detection, location, isolation and restoration. A typical FLISR sequence is characterized by the following steps:

1. ***Fault Detection:*** FLISR systems should only proceed after the occurrence of a fault (e.g. short circuit) on the feeder itself or in the facilities that normally supply the feeder. FLISR should not operate when a feeder is de-energized because of manual switching operations or due to a system wide emergency situation that triggers under-frequency or under-voltage load shedding. Commonly a protective relay intelligent electronic devices (IED) is employed to meet this requirement
2. ***Fault Location:*** the next step is to determine the “section” of the feeder where the fault took place. FLISR “sections” refer to portions of the feeder that are bounded by remotely controlled switches. Each switch contains a Faulted Circuit Indicator (FCI) that controls if fault current has recently passed through the switch
3. ***Fault Isolation:*** after the faulted feeder section has been identified, both sides of the fault need to be isolated. FLISR actions are now in charge of issuing a control command to open the switches needed to completely isolate the damage section of the feeder based on the fault location analysis. Generally, FLISR actions are deferred so that standard automatic reclosing sequence has been completed. In this way, it is ensured that feeder reconfiguration by FLISR is only realized following a permanent fault

4. ***Service restoration:*** Once the damage section of the feeder is properly isolated, FLISR tries to restore service to as many “healthy” sections of the feeder as possible by the use of the available sources. Available sources may include the normal source of supply to the feeder as well as any other available backup sources that may be connected to the faulted feeder via normally-open, remotely controlled tie switches that have spare capacity to carry additional load.

A suggestive process flow is that a fault is detected by the SCADA system and the FLISR system is then activated. After a network model is created by the DMS system for the specific fault case, feasible fault location information is processed in order to adopt either a fault location method or a trial connection method. At that instant, a sequence proposal is initiated by the DMS. The sequence proposal incorporates a list of switching devices that need to be controlled as well as the order of implementation. The SCADA executes the switching actions according to the sequence proposal and transmits the outcomes to the DMS system. The last part of the FLISR process consists on making use of the reserve connections so healthy parts of the feeder can be electrized. Once the automation system has been completed, the fault management process can be carried on. Now, the operator may call the field crew to remove the fault from the feeder.

The most important components of FLISR automation are SCADA, automated Sectionalizing Switches (SSWs) and Tie Switches (TSWs) or NOPs, reclosers, and advanced communications [94]. An exhaustive switching operation process flow of the FLISR process is explicated in [86].

4.1.1 Self-healing grid integration

It must be highlighted that a key aspect of automatic FLISR or self-recovery when applied to distribution systems is the need to identify fault locations and if possible anticipate faulting occurrence (self-prevention). Numerous proposals and commercial products are available in this area, and different levels of fault location capabilities are becoming accessible not only on field level devices such as modern microprocessor-based relays and reclosers, but also on DMS [95]. This includes either fault or outage location. Fault location aims at defining precisely faulted feeder components (e.g. pole, distribution line, etc.), while outage location has the goal of identifying the protective device that has operated to isolate the fault. Here, it must be remembered that not all protective devices are monitored in real-time. For that reason, outage location is aimed at assisting the distribution system operator in detecting the operation of this type of devices as well as confirming the operation of those that are controlled in real-time. Given the variety of topological features of distribution feeders and limited real-time information that historically has been available at distribution system level, most proposals for operation of fault or outage location rely on the combined utilization of short-circuit current, power flow, historic reliability indices, heuristics and expert knowledge. These proposals apply diverse methodologies ranging from signal processing and system analysis to computational intelligence for processing the available data and handling uncertainties to identify the most likely fault location. This category of methods has been reviewed elaborately in [96-99].

In view of previous mentioned, the growth of distribution equipment with monitoring capabilities, such as modern reclosers and switches, IEDs such as voltage and current sensors, faulted circuit indicators, DER, and the growing utilization of SCADA and Advance Metering Infrastructure (AMI) is currently permitting utilities to cope with traditional real-time supervision limitations of distribution systems and increased accuracy of fault location algorithms. Further, the growing interest in applying PMUs to distribution systems is expected to provide with an additional high-definition data source. It seems evident that the consolidation and analysis of these diverse and unsynchronized data sources represent a challenge itself. The fault anticipation concept, on the other side, has been studied in numerous publications and experimental results have been promising. However, wider practical implementation has not been reached yet [100, 101].

Regarding service restoration as such, this is defined as searching suitable backup feeders and laterals to convert the load in out-of-service areas using operational criteria through a series of switching operations [102]. Performing the restoration task under emergency situations makes it time-limited and a complex issue [102, 103]. As already explained, self-healing represent the heart of the smart grid, and involves a system that when subjected to a fault, automatically and intelligently performs corrective actions to restore the system to the best possible state. Hence, such capability to quickly and flexibly reconfigure the network to restore de-energized loads due to a fault represents an essential component of self-healing function. At present, the approaches employed to solve this problem [104]; heuristics, expert system, meta-heuristics, and mathematical programming, operate in a centralized fashion in such a way that a central optimization solver is required to read all the system data before processing them and subsequently finding the solution [105, 106].

The heuristic approach is intuitively rule thumb in order to restrict the search space [107]. The expert´s knowledge and experience are translated into programming logic to solve the problem. Main drawbacks presented by this approach are that optimal solution is not guaranteed, plus they have great difficulties in maintaining the software as the size of the software is large and involves a complex algorithm [108]. Expert system is basically a knowledge-based technique. It comprises the representation of expert knowledge as rules and an inference engine to infer form these rules. The rules are written using IF-THEN statements. Expert system approaches are considered successful approaches to find a solution for the restoration problem. Nevertheless, maintenance of large-scale expert systems can be costly. Additionally, expert system rules are system specific, and they change with the system [108]. Soft computing methods include neutral networks, genetic algorithm, fuzzy theory, tabu search, particle swarm optimization, simulating annealing, and ant colony. Even though these methods are employed to solve large-scale combinatorial optimization problems, they still necessitate larger computational time when applied for distribution system restoration solutions. Moreover, they require a load flow program to keep under control the constrains of the operation [108]. Another approach is mathematical programming. This approach formulates the problem as a Mixed Integer Non-Linear Problem (MINLP) for restoration. Each branch is represented by a binary variable (0: opened & 1: closed). Other constrains such as supply and demand balance are realized in terms of continuous variables. Notwithstanding this approach is able to obtain optimal solutions under operational constrains, the computation time frequently exceeds the practically allocated time due the fact of the combinatorial expansion problem. The computational time increases exponentially with the sized of the de-energized area [108]. Multi-agent systems are another solution and one of the most interesting new fields of computer science and distributed artificial intelligence. For most of the cases, the corrective actions are performed manually by human operators who are in charge of locating, isolating, and implementing the necessary switching operations. This process may take longer as compared to the self-healing capability of the smart grid which will be able to detect and reconfigure the network automatically [109].

Lately, multi-agent systems can be regarded as a leading form of distributed processing, parallel operation, and autonomous solving. It can solve discrete and nonlinear problems in a much faster way, [110] and thus represent an interesting candidate for restoration and control of the distribution system to realize the self-healing operation [111].

4.2 Self-healing grid architecture

An important consideration for self-healing application in distribution systems is selecting the most suitable DA system structure. There are numerous ways in which DA functionalities can be utilized. Proposals range from centralized approaches, where data are gathered and processed at the distribution operation center or distribution substation level, to local approaches which are based on processing and analysis at feeder or device level (peer-to-peer). Each proposal has advantages and disadvantages and there are plenty of commercial products that utilize either approach [69, 112]. Local processing via hierarchical utilization of “agents” is seeing increasing interest and support. Similarly, hybrid approaches such as local implementation of self-restoration combined with centralized processing and analysis have been explored as well [50].

Antila et al. have researched upon DA for MV networks with three solutions [113]:

- Centralized automation model
- Total automation model (combination of centralized and local automation)
- Protection model (only for ring networks).

Coster et al. have discussed a similar solution for the SHG which can be implemented in various forms [114]:

- Centralized solution
- Decentralized solution
- Distributed solution.

These are illustrated in *Figure 4-1* below [115]:

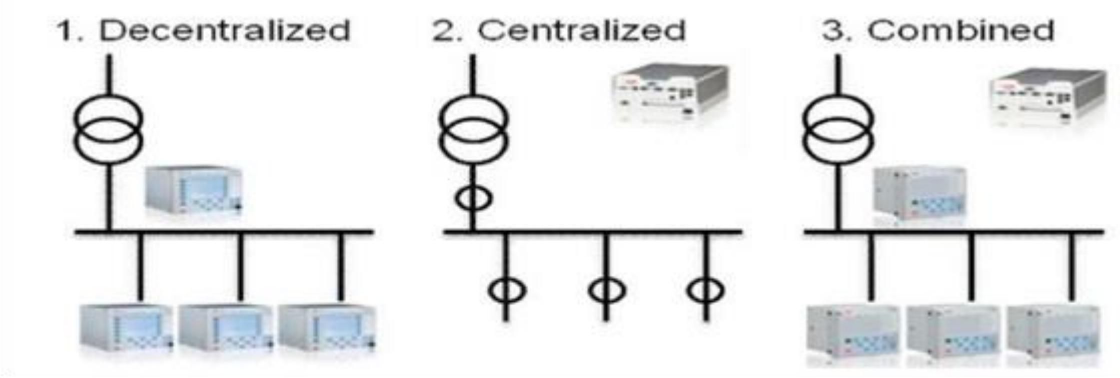

Figure 4-1: Possible architectures for primary substations [115]

4.2.1 Centralized FDIR systems (C-FDIR)

In centralized solutions, the SHG algorithm resides on the DMS which is located in the control center. The SCADA/DMS system concentrates all the modelling, maintenance and intelligence. The solution relies on telemetry and remote control for automatic network operation (FLISR also provides manual switching when applicable), besides power applications. Control options are able to analyze multiple faults across a wide area by running a complete overall network model. In the centralized control, the control center collects the data from all secondary substations and then sends the command for isolating the faulty section. Regarding data process, the communications are started from the control center to the primary substation, then to the secondary substation and so on until the faulted section is reached in order to call the data of a certain secondary substation. Accordingly, the data of the secondary substation is transferred back to the control center and processed by the NIS.

Centralized approach can be implemented as one of the applications of the DMS and utilize SCADA-enabled switches and sensors located at key points in the distribution system to detect an outage, locate the faulted area, isolate the fault, and restore service to unfaulty areas. Depending on the capabilities of the IEDS and sectionalizing devices, and on the speed of SCADA system, communications switching operations may be performed automatically. In centralized FLISR systems, secure, reliable two-way data communication and powerful central are essential. Point-to-point or point-to-multipoint communication is utilized with data collected in the distribution substations and then transmitted to the FLISR system. After, the FLISR system collects the response from each substation and IED issuing a corresponding restoration command. Centralized FLISR systems require a large amount of bandwidth data to operate as the addition of devices on the system produces abeyance and increased restoration time as the system collects data from devices.

Although centralized FLISR systems can be the most costly [116] (the DMS system may be high but the cost per substation automated is relatively low), they can have the longest deployment time. In addition, switching of all signals has to be communicated to the control center, which adds latency and requires high bandwidth communication. On the other hand, other DA applications such as automatic Volt/Var control and optimal feeder reconfiguration can be implemented efficiently under the centralized architecture.

An example of such system is revealed in [47] and case study 2 and 5 are carefully exemplified for further understating of this scheme.

4.2.2 De-centralized FDIR systems (DC-FDIR)

As *Figure 4-2* shows, there are three information hierarchies. These are the control center level, primary substation level and secondary substation level. Fault management using decentralized control strategy is applied on the secondary substation level where the switches (or reclosers) can locally be controlled by the primary substation controller. In order to achieve the coordination with other secondary substations, each secondary substation is able to communicate with neighboring substations.

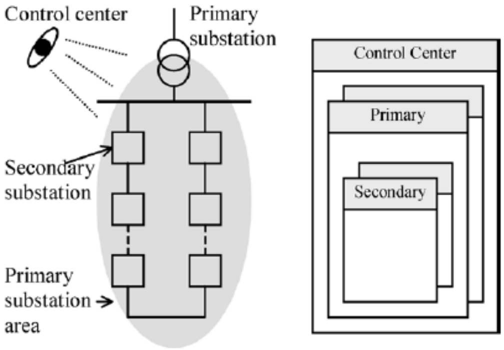

Figure 4-2: View of the design concept component and the corresponding information access hierarchy [116]

In de-centralized FLISR (DC-FDIR) solutions, sometimes referred as substation-centric or substation-based approaches [47], the SHG algorithm is deployed at the primary substation level using a single automation device installed in each substation. In this approach, the remote I/O modules installed at each switch/recloser need to be connected to the distribution substation automation device over communication network.

This solution grants interoperability, supporting switches, reclosers and RTU vendors, assuring adaptability to any real-time network configuration, including also any protection or automation plans. Even though the operation area is restricted to the neighboring of the substation where the substation-centric solution performs its operations, it has the capability to dynamically derive complex restoration solutions including multiple feeders to achieve optimal restoration, covering a specific Distribution Grid Area (DGA) and offering flexibility for DG, storage, and Electric Mobility (EM) penetration. With substation-based FLISR systems, considerable load is dropped when substation breakers are used for fault interruption. When reclosers are used for fault interruption, the protection and sectionalization schemes of the IEDs must be determined before the system can begin service restoration. After these have been completed, the FLISR system polls the IEDs in the same way as in the centralized system, collecting data on the current status of each switch before issuing a restoration command. Unlike a centralized FLISR system, a DC-FLISR system cannot be included to the DMS.

In these type of schemes, adding communication equipment, control power, and substation control can result extremely expensive if not already available at the substations. Furthermore, setting up substation-based FLISR systems can be complicated to expand, and lengthy to implement (depending on the selected IEDs, communication, and desired extent of integration with the existing SCADA system).

4.2.3 Distribution-intelligence FDIR systems (D-FDIR)

The distributed approach (D-FDIR), also referred as fully decentralized [117] schemes, uses controlled devices at each switch or recloser location. These devices communicate among each other in order to determine where the fault occurred and to carry out the appropriate switching actions necessary for the restoration process. In the D-FDIR approach no longer remote I/O remote units are needed but controller at each switch location. Consequently, reliability of this scheme is higher as compared with other approaches since controllers (intelligent devices) are distributed over the network. An example of this solution can be found in [117].

FLISR systems with distributed intelligence and mesh networking are the simplest to configure and fastest to deploy. They can straightforwardly be integrated into the existing SCADA or distribution system. Also, fault detection and sectionalization devices can readily be integrated and operate faster than centralized or substation-based FLISR systems. Distributed-intelligence FLISR systems offer a high degree of innovation. They operate in seconds and can easily be set up with the ability to re-route power and shed unnecessary (“self-heal” ability) load under multi-contingency situations. It seems that distributed-intelligence systems are the easiest to expand along with the requirement growth and as the budget allows. With mesh network communication, each device is able to communicate to each other. Further, backup systems are installed into the communication paths, providing self-healing capability for the communication network in case one or more components of the mesh become inoperable.

Distributed-intelligence FLISR systems enable safety features too in order to prevent automated switching while crews are working on the feeders. This solution can result cost-effective especially when only few switching devices are employed on a restricted area, using a dedicated communication infrastructure. However, distribution approaches are not able to operate under non-standard network topology and is unable to deal with multiple faults. Further, it lacks flexibility for applications as DG, storage or electric mobility penetration [47].

Unlike centralized FLISR system, D-FLISR solutions can be utilized without the need of DMS or GIS implementation. Extensive data collection from the GIS is not needed as in the centralized approach and control in the distribution substation is not required. Distributed-intelligence FLISR systems are entire compatible with SCADA systems, even though SCADA is not necessary to govern D-FLISR systems. Distributed-intelligence FLISR systems need the distribution of IEDs out on the line. In many cases, the control software can be set up on the existing equipment through the addition of an interface control module. If the DMS is utilized, implementing a distributed-intelligence FLISR system will simplify bandwidth and processing of power, and will provide power flow analysis and other functions that require more data, time, and data processing time. The IEC 61850 GOOSE based peer-to-peer communication technology is a good fit for such application which will be carefully detailed in *section 4.3.2* as an application of D-FDIR. A proposed FLISR distributed algorithm using IEC 61850 protocol for transferring status information between the neighboring circuit breakers is also denoted in [118].

A pilot project implementing a fully decentralized scheme was carried out in the city of Rotterdam in the Netherlands. Detailed information about this project and thus this architecture, can be found in [117, 119] as well as in case study 4.

4.2.4 Combined centralized monitor SCADA/DMS with decentralized solutions

In this section, we will describe a method for leveraging the advantages depicted in previous sections; by combining a centralized monitor DMS (SCADA/DMS) with decentralized self-healing strategies for radial operation of open-meshed distribution networks.

Self-healing implicates more than simply providing the maximum degree of reliability indicators as a result of faulted conditions, since it will also require dealing with the new emergent power assets: DG, EM and storage. Global awareness of the full network conditions occurs only at SCADA/DMS level. Hence, where possible constrains may apply;

substation feeders have full flexibility to secure adjacent sections of the network. With increasing penetration of DG, EM and storage, it will be possible to have a complete picture of their impact over the network only at a higher level.

The nature of upstream and downstream recovery of a faulty section deals with the topologically connected remote controlled switches and reclosers and the capacity of adjacent areas to participate in this process. Yet, if we add the complexity of DG injecting intermittent power into the network, as well as of storing temporary power, or demand side management, then the role of adjacent areas may be strongly enlarged. Latency is a key aspect of self-healing: the higher the decision level for remedial actions, the slowest the action [47].

When dealing with a large volume of data, some inaccuracies may occur. Thus, this data needs to be synchronized and available for the operational management processes, difficulting the decision making process. Decentralized self-healing solutions are able to respond faster to any faulty conditions, with local awareness of the network. However, their scope of action is strictly local. In addition, it necessitates coping with a broad number (limited to a certain extent) of substation feeders, tie-points, switches, reclosers and protection schemes. Also, it needs to keep into account any other mixture of RTU, IED and automation controllers participating in the network, besides DG, EM and storage.

A DGA is an operational area determined by one or more substations and their feeders, with possibility of automatic reconfiguration in the event of a fault [47]. Within this area, it is possible to restore non-supplied loads executing few switching actions to carry out load transfer between feeders. The entire distribution network is, hence, the sum of all DGA. The utility will only play the role of defining the granularity level and type of DGA. An illustration of several DGA is displayed in *Figure 4-3* next.

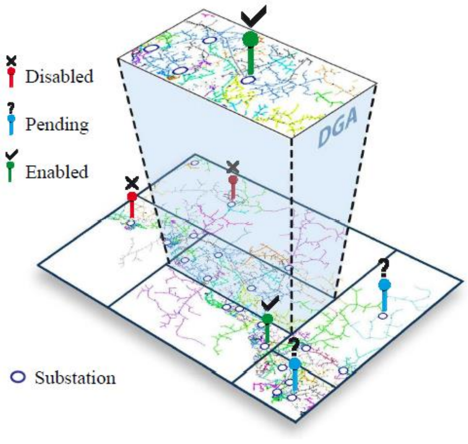

Figure 4-3: Representation of several DGA and their status [47]

Adjacent DGA shares data belonging to any common border. Each DGA may include several substations and their interconnected branches and equipment, where the role of master substation is assigned to one of those. This master substation is provided with a Substation Automation System (SAS). Moreover, another system running the local network model and responsible for implementing self-healing and any kind of DA feature is employed. This system uses real time data acquisition within its own DGA. The master substation´s SAS complementary system is called the Smart Substation Controller (SSC).

The important issue that concerns operators, network architects and utility decision makers is that of the level of trustfulness that substation-centric or even any other local self-healing autonomous process can be allowed when an automatic fault detection, isolation and subsequent restoration plan are to be accomplished. This concern can be loosened if a combined approach is used [47]. Basically, what it means is that SCADA/DMS, besides performing the expected function set, performs preventive actions on a regular basis. For instance, tagging each DGA with a dynamic status as a result of having met the customized criteria. Then, the utility is the one who defines what criterion is, which conditions are to be applied as well as their weight in the tagging process.

A WHAT-IF scenario combining data from every DGA can then be used. This scenario comprises switching state and status data, node voltage and branch current measurements, capacity of the network branches, feeders or transformers, in addition of fault data, power quality, stability and security, potential contingency risks, demand response, adjacent DGA capacity for self-healing support, atmospheric conditions with possible impact on fault occurrence or intermittent DG, or even any other relevant data resulting from system, human or statistical awareness.

A practical implementation of this solution, known as Invogrid project, was deployed by the Portuguese DSO, where main components and services were developed for a fully active distribution network. Technical and detailed details are explained in [47].

4.3 FLISR applicability

Self-healing or self-recovery ranges from conventional approaches such as automatic load transfer and loop sectionalizing to more advanced agent-based restoration schemes, including DER intentional islanding. Self-recovery can be implemented by utilizing only switches (no fault current detection or interrupting capability), only reclosers or a combination of both. The use of switches for conducting self-recovery has the advantages of avoiding issues related to protection coordination that may occur when power flow through a device is reversed due to transferring load to a neighbor feeder. This situation may lead to miscoordination and/or failures in tripping of reclosers. Nevertheless, modern remote-controlled reclosers enable overcoming this problem. These present the inconvenience of having to calculate and program different overcurrent protection settings depending on the potential feeder configurations, but it may be overcome by the implementation of adaptive protection systems. New technologies, including pulse and single-phase reclosing offer additional alternatives for implementing self-restoration schemes. Even though single-phase reclosing allows detecting and isolating just the affected phases in single-phase or two-phase fault conditions, there are practical limitations such as crew safety that avoids implementing this type of operation only to specialized applications.

Driven by the necessity to reduce SAIDI, SAIFI and CAIDI indices to lower levels, utilities are investing in solutions that automatically switch and protect the network with the aim of reducing restoration time trying to eliminate faults or outages from the system. The challenge encountered by utilities is how to optimize the power distribution system with the aim of delivering the greatest reliability while lowering the operation costs and building a modern grid.

Three technologies were selected by ABB to start implementation of smart grid oriented FLISR schemes. Microprocessor controlled reclosers with loop control module logic (restoration logic) based on fault and voltage information combined with timers and alternate setting group enable the achievement of simple and cost effective voltage and current based solutions. On the other and, GOOSE based peer-to-peer solutions solve the problem of speed relying on communication technologies. Last, a substation computer solution in conjunction with the DMS/SCADA may bring better decision based on information from feeders such as power, demand and real time power flow. These are briefed in the coming segments.

4.3.1 FLISR using loop control scheme- voltage and current based solution

Figure 4-4 represents a distribution one-line diagram of a simple loop system that will be used for analysis of the distributed voltage based FLISR scheme.

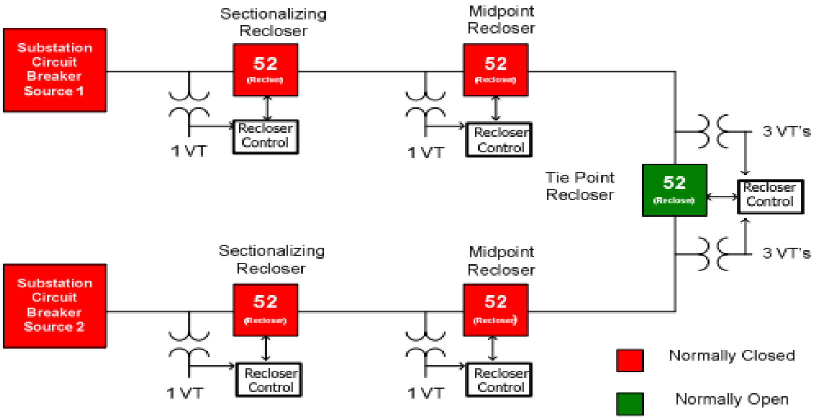

Figure 4-4: Example distribution circuit [120]

This scheme comprises the following elements [120]:

- Source (substation breakers 1 and 2)
- Sectionalizing recloser
- Midpoint recloser
- Tie point recloser.

Source

A source refers to a substation feeder with breaker and auxiliary equipment such as Current Transformers (CTs), IEDs, etc. The substation source is only intended to supply power for the loop control system and it is not generally included in the loop scheme logic system. A loop control system is assumed to have a minimum of two sources. These sources can be supplied by the same or different substation feeder. When selection of these substation, it is recommended that both sources supply same phase rotation power and each source have similar or equal voltage level.

Sectionalizing recloser

The sectionalizing recloser is a typically closed recloser which opens in response to a downstream fault condition or due to a loss of phase voltage from an upstream circuit. The sectionalizer is usually the first protective element on the distribution feeder after the substation.

Midpoint recloser

The midpoint recloser is generally closed too. Different from the sectionalizing recloser, the midpoint recloser does not open in response to phase voltage loss. Instead, it does support loop control by automatically adjusting the IED settings in accordance with varying voltage conditions.

Tie point recloser

The tiepoint recloser, unlike the sectionalizing and midpoint recloser is typically open. It closes in response to a loss of all phase voltages from one source if the phase voltage on the other source prevail/ remain in action. Once the tie point is closed, it may automatically trip if a downstream overcurrent condition happens and is not isolated by the midpoint recloser first. In addition, the tiepoint recloser can be set to apply diverse fault thresholds depending on which side of the loop it is supplying (e.g. which side is downstream).

In a loop configuration, it is easy to notice about the potential fault locations that can be found on each side of the tieopoint recloser. The first possible location for a fault to occur is between the source and sectionalizing recloser. The second section of the line between the sectionalizing and midpoint recloser is the next hot spot. Last, the fault may occur between the midpoint and tiepoint recloser. The sequence restoration process can be described for the case of a permanent fault occurring between the sources and sectionalizing recloser following the next sequence of events.

Assuming that in *Figure 4-4* there is a permanent fault between the source1 circuit breaker and the sectionalizing recloser, the following will happen. The source1 circuit breaker will first recognize the fault and initiate its reclosing actions to lockout (for illustration purposes we will assume three operations to lockout for all devices, see *Figure 4-5*). Sectionalizing recloser will then recognize a loss of voltage after the circuit breaker operation. However, if the voltage does not return for the livebus timer setting, it will automatically trip after t1 seconds as illustrated in *Figure 4-5*, isolating the faulted zone on the source side of the recloser.

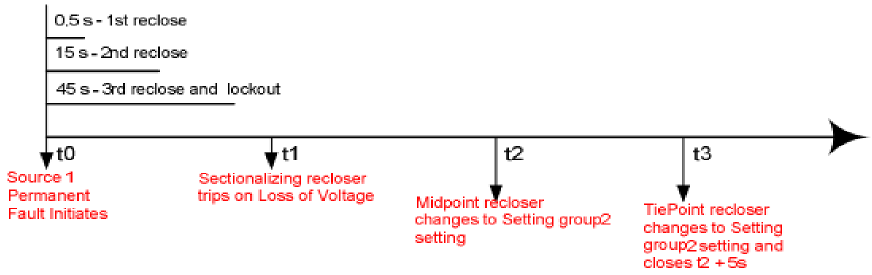

Figure 4-5: Sequence of events [6]

Likewise, the midpoint recloser detects the same voltage loss, and if the voltage does not return for the livebus timer setting, it will request the IED to start its Switch-on-to-fault (SWOTF) timer. Group2 settings may be used if suitably programmed after t2 seconds (typically set about 10 seconds after the sectionalizer is set to lockout).

At the same instant, the tie-point will identify a three phase loss voltage on the source1 side of its recloser Voltage Transformers (VTs). After a time delay of t3 seconds measured from the initial fault at souce1, the tie-point recloser T will close. Once again, group2 settings can be used if suitable programmed. By completing this action, source2 service is initiated.

The non-faulted section of the feeder between the sectionalizing recloser and the tiepoint recloser is adopted as back up.

4.3.2 FLISR using loop control scheme using 61850 peer-to-peer GOOSE based communication

Similarly as before, *Figure 4-6* represents a distribution one-line diagram of a simple loop system that will be used for analysis of FLISR using peer-to-peer communication scheme. This system encompasses the same elements as *Figure 4-4* in previous segment, but the characteristic of this implementation is that recloser controllers in *Figure 4-4* admit IEC

61850 capability. The benefit of employing IEC 61850 is that interoperable Generic Object Oriented Substation Event (GOOSE) messaging between recloser controls can be used. GOOSE data is exchanged between recloser controls at fixed time intervals and is based on a publisher/subscriber model [120].

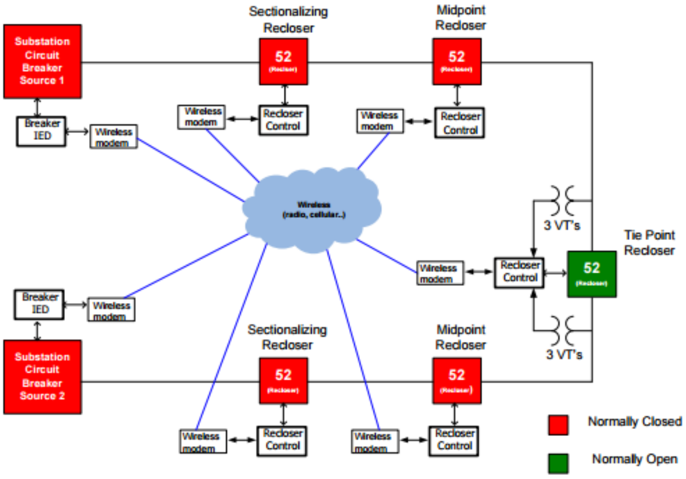

Figure 4-6: Example distribution circuit [120]

IEC 61850 peer-to-peer communication

As it was just stated, all recloser controllers in *Figure 4-4* are IEC 61850 capable, with the benefit of enabling the use of GOOSE messaging. Data sending between recloser controls is event based and when a variation in GOOSE data occurs, a message is transmitted multiple times to the network. Data exchange between recloser controls is based on publisher/subscriber mechanism. The publisher recloser control multicast data over the local area network to several subscriber recloser controls. The content of GOOSE messages is able to receive recloser controls to fulfill processing of the data in order to execute needed actions.

Again, the three potential fault locations are on each side of the tiepoint recloser; between source and sectionalizing recloser, between sectionalizing and midpoint recloser and between midpoint and tiepoint recloser. In this application high speed, peer-to-peer IEC 61850 communication is applied and the distributed FLISR intelligence is performed on each switch/recloser controller. The sequence restoration process can be described for the specific case of a permanent fault occurring between the source and sectionalizing recloser in *Figure 4-6*.

The source1 circuit breaker will detect the fault and go through its reclosing steps to lockout (for illustration purposes 3 operations to lockout will be assumed for all devices). Along with this, source1 circuit breaker will multicast GOOSE messages that involve lockout information. Sectionalizing recloser will then receive a lockout message and it will automatically trip after t1 seconds (see *Figure 4-7*), isolating the faulted zone on the source side of the recloser.

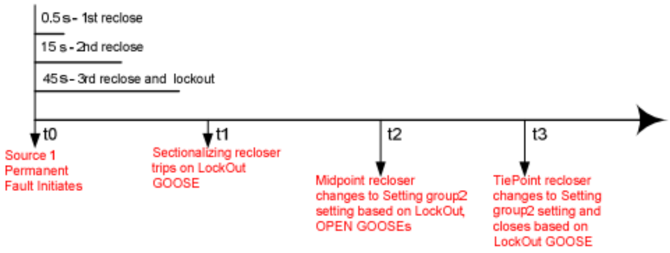

Figure 4-7: Example distribution circuit [120]

To improve the security (by using and advanced logic programming capability in the recloser control) received lockout GOOSE can be verified by other conditions before the open command is sent to the sectionalizing recloser (*see Figure 4-8*):

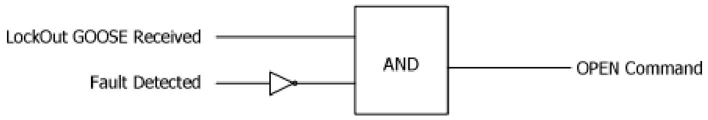

Figure 4-8: Figure of logic for sectionalizing recloser [120]

Lockout GOOSE from source1 breaker and open position GOOSE from sectionalizing recloser will be used as inputs for midpoint recloser. Two GOOSE messages from source1 breaker and sectionalizing recloser will necessitate the midpoint recloser control to begin its SWOTF timer (*Figure 4-9*). If properly programmed, setting group2 settings can be used after t2 seconds.

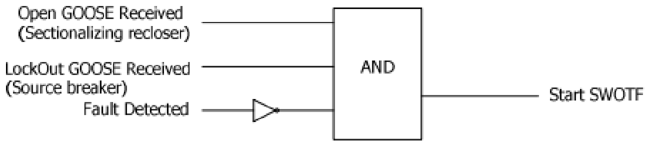

Figure 4-9:Example distribution circuit [120]

Lockout GOOSE from source1 breaker and open position GOOSE form sectionalizing recloser will be used now as inputs for tiepoint recloser. Two GOOSE messages from-source1 breaker and sectionalizing recloser will request the tiepoint recloser control. If properly programmed, setting group2 settings can be used after t3 seconds. To improve the security (by using and advanced logic programming capability in the recloser control) received lock out and open position GOOSE can be verified by other conditions before the close command is sent to tiepoint recloser (see *Figure 4-10*).

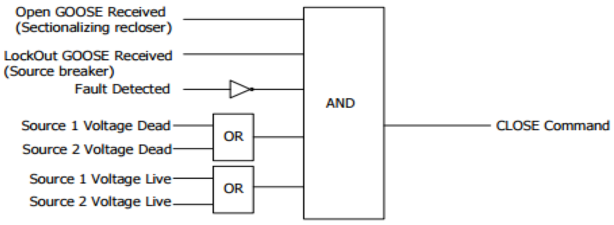

Figure 4-10:Example distribution circuit [120]

The non-faulted portion of the distributed feeder circuit between sectionalizing recloser and tiepoint recloser is picked back up.

4.3.3 FLISR using decentralized scheme

Figure 4-11 represents a distribution one-line diagram that will be used for analysis of FLISR using a decentralized approach.

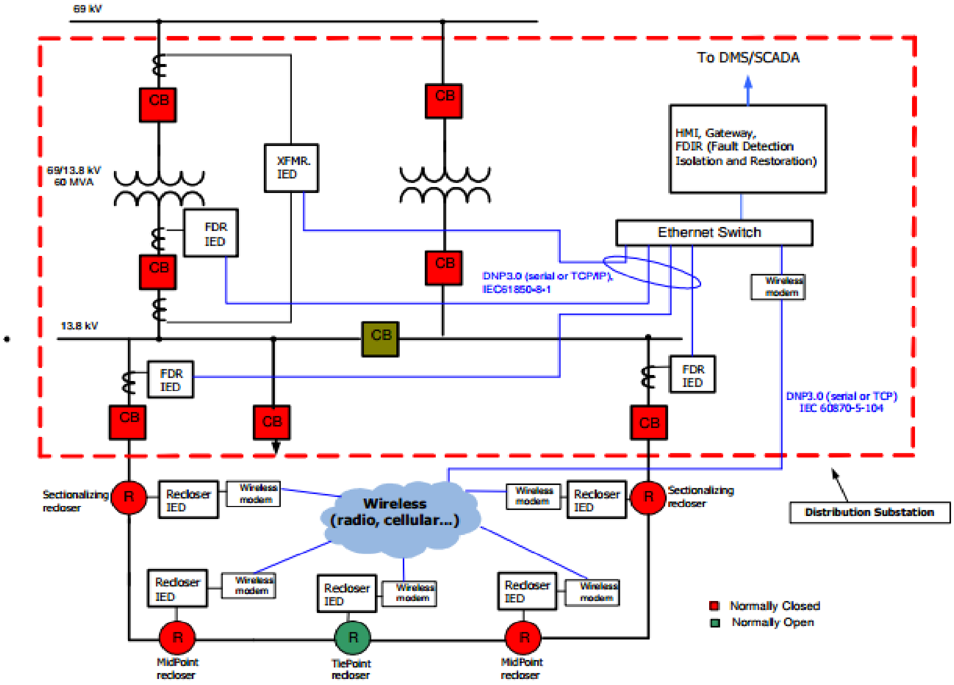

Figure 4-11: Example distribution circuit [120]

This system comprises of the following components:

- Source breakers
- Sectionalizing recloser
- Midpoint recloser
- Tie Point recloser
- Substation HMI, Gateway with FLISR.

Previously most of the components were explained, except the substation HMI, which is referred next, as well as some basic notions that should be known to understand this scheme.

Substation HMI and gateway with FLISR

Substation IEDs are connected to the substation HMI and gateway via ethernet switch as shown in *Figure 4-11*. Also, feeder devices (reclosers from *Figure 4-11*), are connected to the substation HMI and gateway through wireless communication. Substation HMI and gateway can support numerous communication protocols such as IEC 61850. Recloser controllers can also support SCADA. Both SCADA and IEC 61850 protocols can be supported simultaneously too. If necessary, substation HMI and gateway can be connected to the centralized DMS or SCADA systems.

Network Model

For the purpose of decentralized FLISR description, a simplified network model is considered in *Figure 4-11*. As mentioned, three types of components are included: sources, switching devices (e.g. reclosers) and loads. Sources are assumed to have limited capacity (ampere rating) but constant voltage. Switches are assumed to have limited loading capability (in amperes). Loads may be assumed to be constant for analysis purposes.

Network Connectivity

The connectivity of the network model must be acknowledged in order to accomplish successful fault isolation and service restoration. The switching devices, loads, and sources (and the way in which components are connected) are required for the isolation and restoration purpose. By creating a network Single Line Diagram (SLD) of *Figure 4-11* at the substation HMI and gateway, network connectivity is automatically provided to the FLISR that runs on such HMI and gateway.

In this solution, the sequence steps will proceed as follows for the case fault scenario of a fault occurring between sectionalizing and midpoint reclosers:

1. A permanent fault occur on the section between sectionalizing and midpoint reclosers
2. The sectionalizing recloser will recognize the fault and go through its reclosing stept to Lockout (again 3 operations to lockout for all devices will be assumed for illustration purposes)
3. Lockout information from sectionalizing recloser will be sent to the substation HMI and gateway using SCADA protocols (e.g. IEC 61580)
4. Upon receiving the lockout information, FLISR algorithm will fulfill the fault isolation process by sending the open command to the midpoint recloser.
5. The open midpoint recloser will be picked as the “isolation switch” and FLISR will search for the most optimal portion to restore the power to the unserved loads

between midpoint and tiepoint reclosers. In the simple case example displayed in *Figure 4-11*, there is only one part to restore service, i.e. close tiepoint

6. FLISR will send close command to tiepoint recloser. Then, service is restored between midpoint and tiepoint reclosers.

A last remark here is that a restoration switching analysis method generates a sequence that when executed will attain a valid post-restoration network that satisfies the following requirements [6]:

- It is radial
- There is no existing negligence at any network component.

Even though, some other optimization requirements may also be considered in the algorithm, the chosen FLISR scheme at the substation HMI and gateway presents a deterministic algorithm that identifies a restoration strategy to restore the out-of-service load due to fault isolation while ensuring that the post-restoration network has an accurate configuration. The algorithm is based upon the concepts of network tracing and it can handle both single-path and multi-path restoration. In case the network component are too stressed and even the multi-path restoration cannot restore all the out-of-service loads, the algorithm tries to shed minimal load while restoring as many other loads as possible.

4.3.4 FLISR using loop control scheme- substation computer and DMS/SCADA

A combined SCADA and substation computer solution is a more reasonable way to implement a meshed or complex network FDIR scheme. Substation computers are able to be programmed and decisions can be made based upon information from feeder devices. Report of the status and metrics to the SCADA/DMS system is deployed by substation computers. This way an extensive and inclusive view of the network can be achieved in comparison with other approaches. Additionally, the SCADA/DMS can make decisions based on additional factors implicated such as feeder loads, overload conditions and demand response. Combined with the restoration process deployed from the local substation computer, a meshed SCADA and substation computer is capable to decide which devices should be switched to improve the power quality of the overall system, i.e. voltage-var control schemes. The combined SCADA/DMS and local substation computer solution offer broad benefits. From faster feeder level response to an event and scalability through the implementation of future distributed generation into the grid such as energy storage units, electrical vehicles, solar panels to voltage var control. Also reduction in the engineering hours to set each feeder device so to perform FDIR schemes is attained. In the SCADA and substation computer solution, recloser controls do not need to use interoperable communication protocols, as long as the substation computer is able to interface to each recloser control. This is usually the case for utilities that are on the development path to modernize their grid.

In comparison with peer to peer communication, GOOSE based FDIR may be faster (in terms of operating speed) [120]. Nonetheless, the additional information provided by the SCADA/DMS and substation computer application allows FDIR to present a larger view of the system, using all the various factors already mentioned.

4.3.5 FLISR algorithms comparison

Each FLISR algorithm has been compared considering different criteria as displayed in *Table 4-1.*

Table 4-1: Comparison of different FLISR solutions

	External VTs at reclosers	Remote (wireless, wired) communication	Scalability	Existing negligence on reclosers	Operational flexibility
FLISR-Voltage time scheme	YES	NO	LOW	NO	LOW
FLISR- IEC 61850 peer-to-peer scheme	NO	YES	MEDIUM	NO	MEDIUM
FLISR- Substation based scheme	NO	YES	HIGH	YES	HIGH

Voltage and current loop based solution has the advantages of being simple, plus it does not need from communication infrastructure. However, it is limited in its application due to the fact that system loading is not reviewed. Also, closing of an un-faulted source into a faulted source may cause stressing of the system under certain conditions. Peer to peer scheme offers the advantages of restoration using loop control and not closing into a permanent fault from another source. Nevertheless, a communication infrastructure is required. Decentralized offers the most flexibility of all schemes and it can be deployed to a greater number of devices. In addition, it also has the advantage of examination for the current and restoration based on loading at the nodes is possible.

Although each FLISR algorithm contributes to an enhancement of feeder reliability, selection and implementation of the different FLISR solutions depends on many factors. Just to mention a few, smart grid strategy to be considered, communication infrastructure, location recloser infrastructure, conditions needed for each distribution loop, financial costs, and others.

To briefly mention a conclusion drawn from previous applications is that in the simplest scheme the reclosers are able to detect the loss of voltage and after pre-programmed time, the recloser closes. This scheme does not require telecommunication; however it is possible to switch onto a fault. The second presented scheme solves the problem of closing onto a fault, but as a requirement is an advanced GOOSE technology and telecommunication. The third presented solution is a combined substation computer application and SCADA/DMS. The computer application makes a restoration plan based on information on feeder devices. Combined with this restoration plan and other information from the network, the SCADA/DMS can make decision on switching actions. The complexity, budget, and operational philosophy of the utility system will determine the most appropriate solution in order to reach the SAIDI, SAIFI and CAIDI goals. The three solutions introduced in above offer tools for the utilities to address the diverse area's needs and diversify the solutions realized. The technology chosen and the feeder device selection play a vital role for the future deployment of the utility roadmap for achieving a smart grid.

4.3.6 Communication technologies for FLISR solutions

Lastly, it should be remembered the importance of communication technologies for limiting managing complexity. Success of FLISR greatly depends on the reliability and efficiency of the communication technology employed for information exchange between the intelligence devices located along the feeder. At this stage, Power Line Communication (PLC) may not be the most appropriate for FLISR application, as the feeder line section would be isolated.

In the recent report on National Institute of Standard and Technology (NIST) framework and roadmap for smart grid interoperability standards [121], some wired and wireless communication technologies are presented for smart grid applications.

Table 4-2. Potential wireless technologies [26]

Wireless technology	Data rate	Approx. Coverage
Wireless LAN	1-54Mbps	100m (repeater may increase the coverage)
WiMAX	70Mbps	48Km
Cellular	60-240Kbps	10-50Km
Spread spectrum radio (900 MHz)	106Kbps	Up to 50Km with repeater

Implementation of wireless technology in FLISR offers many advantages in comparison with wired such as the low installation cost, mobility, remote location coverage, rapid installation, etc. Nonetheless, each technology has certain challenges and limitations. Some of those concerns include the susceptibility of wireless technologies operating in unlicensed frequency to interference and noise effects. Additionally, wireless technologies with licensed spectrum have less interference, but they are a costly solution and even security of wireless media may be lower. Further discussion on these technologies can obtained from [122, 123].

4.4 Decentralized agent-based control

As it has been reported, the remote control strategy of the automatic switches can be roughly categorized into centralized or decentralized (distributed) control, with its own benefits and drawbacks as it was explained throughout previous chapters.

Distributed agent-based control is a decentralized control methodology starting from the primary substation until the faulty section is localized after the breaker disconnection, and depending on the interchanged data between each two consecutive secondary substations. Distributed agent-based decentralized control is presented in [81, 83]. To get an idea of this control, *Figure 4-12* shows two neighboring secondary substations *m*-1 and *m* with a faulty section in-between.

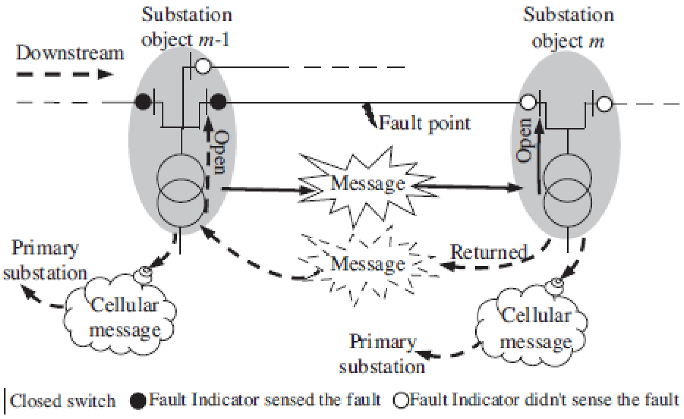

Figure 4-12: Schematic of autonomous agent-based control [116]

The fault management process starts when the breaker disconnects the feeder and consequently the voltage on the section ceases. This control action depends on tokens transmitted between the secondary substations starting from the primary substation. A downstream token is sent to secondary substations until the faulty section is identified as shown in *Figure 4-12*. This automated fault management process has been detailed in [83] in seven basic steps as follows:

- Step1: a token from the primary substation is communicated to the adjacent secondary substation so the fault management process can be initiated
- Step 2: at the secondary substation, the fault indicator status is evaluated. If a fault is identified, the toke is communicated to the next substation. This step is continuously repeated in the following secondary substation until a substation does not

detect the fault. This substation will be the first one after the faulty section, as illustrated in *Figure 4-12*. As a result, the faulty section has been recognized
- Step 3: a token from the substation behind the fault is sent back to the substation just before the fault perceiving the faulty section; hence, both substations open their switches
- Step 4: an upstream token is consequently transmitted between the secondary substations back to the primary substation claiming the fault identification and the need for power
- Step 5: a token is transmitted to the backup primary substation claiming the need of power
- Step 6: a token is now sent between the secondary substations that are connected by the backup primary substation in order to close the appropriate switch to energize the substations behind the isolated faulty section
- Step 7: updated information about the event and the new circuit configuration reaches the control center.

As can be seen, it can be concluded that the fault management using the centralized control starts from and under full control of the control center whereas the decentralized control starts from the primary substation. Yet, the decision for isolating the fault is decentralized; the fault management start is still begun from the high level and thus is able to evaluate the secondary substation objects that can delay the fault isolation process.

Distributed agent fault management control strategy has been reported in many research articles. Baxevanos et al. have carried out an extended research upon the potential of implementing distributed intelligence technology to achieve high degrees of independency in the distribution network [58]. In [56], Nordman et al. proposed a concept based on local agents for state estimation of electrical distribution systems. Decentralized agent based control has been implemented with the purpose of achieving several aims such as state estimation, system monitoring fault management and power systems restoration. Zhabelova et al. presented a multiagent smart grid automation architecture based on IEC 61850/61499 which supports distributed multiagent intelligence, interoperability, and configurability and enables efficient simulation of distributed automation systems [59]. In [91], authors modelled a conceptual design to dynamically manage agents in power systems with a flexible coordination structure to overcome the limitations of centralized and decentralized solution strategies. Even Nguyen et al. makes use of agents, which possess three key characteristics, namely autonomy, local view, and decentralization to present a distributed algorithm for service restoration with distributed energy storage support following fault detection, location, and isolation [92].

Decentralized agent based control has been implemented with the purpose of achieving several aims such as state estimation, system monitoring fault management and power systems restoration.The proposed scheme divides the distribution system into zones or layers, which indicates a segment of a distribution feeder that is bounded by two or more switches. These are represented as agents. Associated with these applications, distributed agents like: feeder terminal unit agents, transformer agents, circuit breaker agents, etc., are responsible of performing local and remote control functions. In *section 4.5*, this concept is developed under the notion of the zone concept [124].

Figure 4-12 illustrates the basic core of an autonomous agent-based control, where both two neighboring secondary substations *m-1* and *m* communicate together. Thereupon, both substations are allowed to carry out their own decision whenever a fault occurred between them.

Here, the fault management process is independently from the primary substations. However, the secondary substation is activated to participate in the fault management process taking into account two conditions; that the voltage has disappeared and its fault indicator detects the fault. These two conditions are achieved in the secondary substations that are located before the fault point. Then, each agent of these substations will send a simultaneous and independent fault message to the neighbor downstream substation in the direction of the fault. For example at substation *m*-1 shown in *Figure 4-12,* the message transmits in the direction of substation *m* as its branch indicator is the one that detects the fault. In other words, for substation *m*-1, there are three branches whereas two fault indicators are used to detect the fault; one is upstream of the substation and the other is downstream at the fault direction. However, the third one does not sense the fault occurrence because the fault is not at its downstream direction. Consequently, the message goes to substation *m*. Each substation, which is located before the fault, normally receives this message and consequently the faulty section is not identified until its fault indicator detects the fault. Another case arises when the substation receives a message, but its fault indicator does not detect the fault as shown in *Figure 4-12* in substation *m*. In this case, the faulty section is detected and the action to isolate the fault has to be activated with the aid of a return message. Subsequently, fault isolation occurs, and then a message from each secondary substation at the faulty section terminals is directly sent to the primary substation in order to reclose the breaker and restore the healthy parts.

This needs a direct communication between the secondary substations and the higher level stations. Feeder Terminal Units (FTU) applications are addressed in [78] demonstrating this process. Another example is described in [125], where the direct connection between the distributed secondary substations with the primary substation is realized using cellular modem at the secondary substations in order to communicate over a mobile telephone network. Even though such a direct communication of each secondary substation to the higher level raises the cost, faster time response and better reliability are attained.

The chart shown in *Figure 4-13* details the control steps that were proposed for the secondary substation to complete the intended control actions.

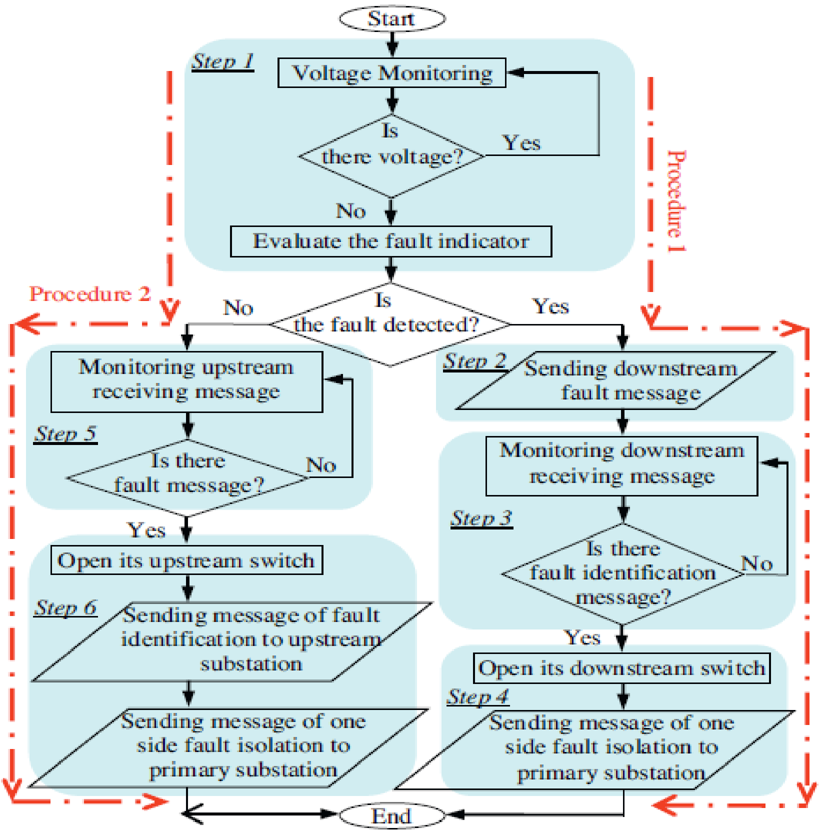

Figure 4-13: Procedure of the substation agent for an autonomous control [116]

Two major procedures are assigned for each substation upon detection of the occurring fault and the relative position of the substation. If a low voltage condition is recognized via step 1, either procedure 1 or 2 is started upon the status of the utilized fault indicators. In case that the substation is located before the fault point, its response is begun according to procedure 1 through steps 1, 2 and 3. On the other hand, procedure 2 is initiated for the substations after the fault point through steps 5 and 6. For a detected fault scenario, procedure 1 is initiated by sending a downstream fault message. In step 3, a waiting loop is stopped upon reception of a fault message indicating a faulty section. Nevertheless, this message can be discarded when the voltage is restored at the substation once again. Also, the voltage restoration may be a condition to conclude the fault management and to restart the subroutine of waiting for another fault management case. Likewise, looping via step 5 is stopped upon reception of a fault message. In this case, if the primary substation has received two messages of faulty section identification and two switches remain opened, healthy part are restored. Then, an updated version of the event takes place and the new circuit configuration is updated at the control center [116].

4.4.1 Multi-agent systems for FLISR applications

MAS are one of the most interesting new fields of computer science and distributed artificial intelligence. MAS can be defined as a computational system in which several agents cooperate and coordinate with each other to accomplish organizational objectives in a decentralized manner [126]. These agents react to variations in the environment and are capable of acting (making decisions) in order to achieve specified goals [127]. A multiagent system can be considered the collective method of distributed processing, parallel operation, and autonomous solving. It can also be much faster for solving discrete and nonlinear problems [110]. This technology is superior to centralized schemes mentioned above since even if a part of the system fails the rest of the system remains under working conditions.

Generally, agent refers to an entity with active behavioral capacity in any environment, such as organism, software system or controller in control system [128]. As above described, MAS is a loose coupling network constituted by several agents. Physically or logically the agents are distributed, and their behaviors would not be restricted by any other agents. To achieve the same task or the same goal, all the agents are connected to each other under some kind of protocol. They have the competence to solve problems beyond single agent´s capability by communication and cooperation. MAS should be required for applications which exhibit at least one of the following characteristics. The demand for interaction between different conceptual entities where difficulties to clearly model an overall system behavior may be encountered; the locally available data is sufficient to allow decision-making without an external central facilitator (e.g. substation-based diagnostics and analysis systems); or either new functions are needed to be implemented within existing plant items and control systems (e.g. extending substation-based condition monitoring systems) by adding data interpretation functions [129].

As an example to easy comprehend this approach, regional autonomy of multiagents can easily show the working structure of agents. This is shown in
Figure 4-14, where a re-gional feeder multiagent network model is illustrated. This results from dividing the over-all network into several feeder units. Each one of those is regarded as a regional feeder agent. Considering regional autonomy of multiagent, the set of non-switch devices con-trolled by switch devices on the same regional feeder (including generators, loads, switches, etc.) can be referred as one agent. In accordance, a given overall network can be divided in separate power supply agents as shown in
Figure 4-14.

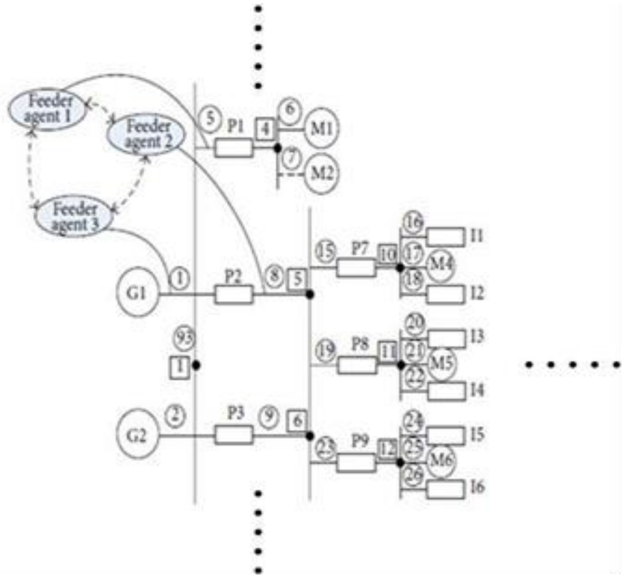

Figure 4-14: Regional feeder multiagent network [128]

Recently, extensive research has been carried out on MAS technology aiming to find solutions in the field of power systems and other fields. In [2, 130, 131] authors have proposed decentralized MAS architectures for automated FLISR. Authors in [132] have proposed an artificial immune system algorithm for the fault restoration problem. In [133] the author showed a practical implementation of MAS for FLISR in which agents are implemented in microprocessors and the distribution system is simulated by means of a power system simulator. Authors in [127] have designed a decentralized MAS architecture for fault restoration in microgrids. In [94], a hybrid MAS fault restoration scheme is proposed that will work for distribution network with microgrids to overcome the drawback of both decentralized and centralized solutions. In [134], a two-stage distributed method for the restoration problem using multi-agent system is employed involving two stages in the restoration process and incorporating four types of agents.

4.4.2 Application of MAS in network reconfiguration of a distribution network

As has been mentioned throughout the work, in the distribution network fault management, service restoration is a very important unit. When a fault takes place, it is necessary to restore power to these de-energized loads as fast as possible. The restoration problem could be formulated as a multi-level, multi-objective optimization level with constrains [135]. Commonly, the approaches to study service restoration in distribution system can be roughly gathered into two categories: centralized methods and distributed methods. Centralized methods [136-139] include heuristic approaches, Expert Systems (ESs), and Mathematical Programming (MP), while distributed methods are mainly based on MAS technology. It is worthwhile to note that major limitations of centralized methods are that these approaches normally depend on a powerful central facility to handle extremely large amount of data to handle extremely large amount of data with high communication capability requirement; hence such approaches tend to lead to single point of failure [140]. To this end, distributed methods such as agent-based approaches have received significantly increased attention recently in the community to handle the complex power system research and development [141-145].

In order to address new emerging power assets in the smart grid environment: DG, EM and storage the following architecture will now concentrate on the agent-based method for service restoration problem with the integration of DGs. Amongst the many efforts of using agent-based approaches to support the smart grid development, it has been documented that service restoration problem is a highly essential. Nagata et al. proposed several multi-agent system approaches for service restoration of distribution systems [146-148], where a special agent was selected to dispatch and manage other agents for the whole system. Equally, Solanki et al. proposed a fully decentralized multi-agent system to restore the power supply to the de-energized loads, and also established the interface between MAS and power system simulation software by FIPA compliant language [2].

The impact of DG technology for the power system is twofold. On one hand, it can improve the reliability and efficiency of distribution system. On the other hand, it could also generate negative influence on distribution system restoration. Adding the complexity of DG injecting intermittent power into the network as well as of temporary stored power will add latency. As already indicated in earlier chapters, this is a key aspect of self-healing as the higher is the decision level for corrective actions, the slower the will be the action. In general, the structure of traditional distribution system is radial. In such networks, the power flow on any feeder is one-way. However, with the integration of DGs into such systems, the power flow on some feeders will turn into bi-directional. Consequently, large-scale incorporation of DGs in distribution systems has made it progressively necessary to develop restoration schemes when integrated with DGs [1, 149]. Additionally to the hereby proposed decentralized agent-based solution via MAS to tackle the complexity of power recovery when penetration of DG, next a real practical solution based on sectioning the network into smaller zones is described.

4.5 FLISR using the zone concept

The *zone concept* refers to a systematic method of dividing distribution networks into manageable areas (zones) based on loads, load criticality and disturbance vulnerability, similarly to what it was just explained above [150]. Accordingly, the differences in fault vulnerability between one zone and other zones along with the priority of the loads determine the required automation level.

In the zone concept, the lay-out of the power distribution network is affected by the density of settlement, the power consumption and its criticality, legislation, environmental concerns, weather conditions, philosophy of the distribution network etc.

Figure 4-15 shows different network zones downstream of the substation as shadowed areas. Between these zones dividers with protection and breaking/reclosing or just disconnecting capabilities are introduced. All zone dividers are equipped with remote communication for transfer of status indications, control commands, measurements, etc. required by the application. Depending on the capability of the zone divider equipment, the zone on the downside constitutes either a protection zone or a control zone. Nowadays, the ongoing share of distributed energy resources put special demands on the flexibility and adaptability of the equipment functionality.

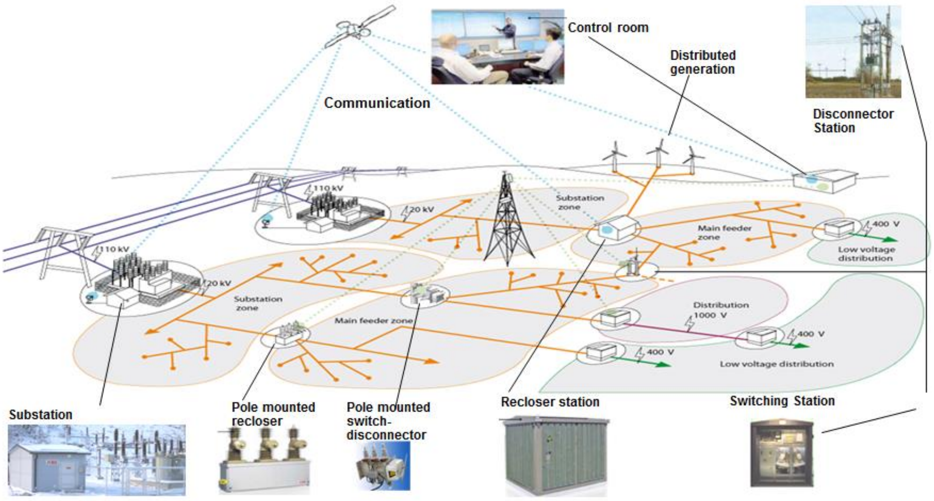

Figure 4-15: Main principles of the zone concept [150]

The zone concept involves two main functions which are *protection* and *control* as illustrated in *Figure 4-16* below:

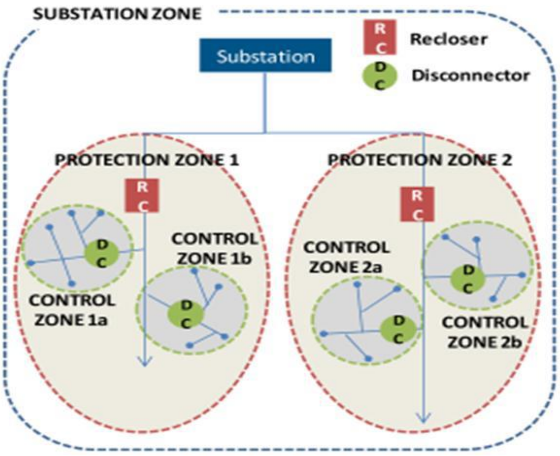

Figure 4-16: Example of zone protection [151]

These two functions are applied to the outgoing MV feeder to form either a protection zone or a control zone based on the capability of the zone divider and the necessity to protect the supply to areas with significant critical consumption. Each protection zone with one principal incoming feeder has several lateral outgoing feeders which may have an impact along the entire feeder as well as in the connected consumers too. The zone concept functions by integrating protection and reclosing functions. The process works in such a way that interruptions on other sections of the network are avoided by conducting reclosing functions and interruptions to the selective parts of the network where the fault exits by creating sections or zones.

The key components included for the zone concept are CBs and SD as zone dividers for protection and breakering/reclosing or just for disconnecting capabilities. Other advanced components utilized comprise of line reclosers (CB equipped with automatically closing mechanism), automatic sectionalizer and RCDs. Depending on the necessity, it can also contain distributed compensation equipment. For achieving more developed automation, communication equipment for connecting with upper level system is also required [150]. This provides remote communication capability for sharing of status indications, measurement, control commands and other information needed by the application.

The practical experience of this self-healing power system by means of the zone concept is explained in case study 3.

5. IMPLEMENTATION CASE STUDIES OF SELF-HEALING GRID

As it was remarked throughout the work, self-healing strategies are an inherent part of the smart grid concept and are expected to play a fundamental role in modern and future distribution systems. It is worthwhile highlighting the importance of switch-gear technology (protective and switching devices), sensors, enterprise systems and communication infrastructures that are needed for the implementation of self-healing strategies. As matter of that, a growing number of self-healing projects are being implemented worldwide by different network operators as part of their power delivery modernization plans: *Masala pilot project by Fortrum* [120], *Case Elenia* [86], and demonstrated project by *Helen power* corporation[51] in Finland, DONG Energy project in Denmark [152], *Steiden* pilot project in the Netherlands *[117, 119], the Smart Peninsula* pilot project in Poland [153], *InovCity* in Portugal [47], *Scottish and Southern Energy (SSE)* project in Scotland [154]. Also especial attention was given in the USA with numerous projects developed by networks utilities such as *Nelson Bay* [155], *NRECA* [156], *Jackson Purchase Energy Corporation (JPEC*) [48]. In Canada, *ENMAX* Power corporation [157] *and Power Stream* [158] utilities established pilot cases too. Last but not least, Middle East, *Electricity and Water Authority (DEWA)* [89] and Australia, *Ausgrid* [159] utilities have given rise to the utilization of the self-healing grid.

For practical aspects, the case studies of projects that have already been executed, to some extent, utilize concepts similar to the formerly studied. 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.

5.1 Case study 1

Elenia´s distribution network is a rural network consisting of 1024 km of 110 kV lines, 135 pcs of 110/20 kV primary substations, 22 050 km of 20 kV lines, 21 523 pcs of 20/0.4 kV distribution transformers and 38 626 km of 0.4 kV lines. Apart from the remotely operated primary substations, Elenia´s network is equipped with 3500 remotely operated disconnectors and breakers to achieve efficient and centralized outage management. Elenia has 408 000 customers, and of these approximately 374 000 are connected to FLISR automated network. [86]

Case Elenia, the first implementation of FDIR, is presented here as a proof of concept. At Elenia, FLISR is used in the entire medium voltage network apart from few specified feeder with critical industrial customers. After site acceptance testing period of six months, FLISR has been in production use at Elenia since October 2011, at first in manual confirmation mode and switched to auto confirmation mode already in December 2011. Since then, DSO operations managed numerous power outages, both occasional incidents and major disturbances, even with hundreds of simultaneous medium voltages outages. The first year experiences are very promising. Firstly, no harmful situations were detected as a consequence of the automation. In total, 382 FLISR cases were executed successfully in 2012. As expected, quite a large number of other cases were aborted during the execution because of recurring problems in the mechanics and telecommunication of old dense-roll sectionalizers. In certain circumstances, execution of the sequences revealed data quality issues (either on the SCADA or DMS side). These turned out to be naturally less frequent after corrective actions by DSO personnel. Elenia is determined to raise the utilization, efficiency and reliability of the automation by further developing the functionality together with software partners. This pilot case served as a study lesson for further projects in Finland which are explained next. [86]

5.2 Case study 2

Helen Electricity Network Ltd. (Helen) is responsible for the electricity distribution in Helsinki, the capital area of Finland. Helen has about 365 000 customers, among them a lot of government buildings, head offices and companies with high financial value and heavy flow of customers. Prior studies in [160] indicated that the Customer Interruption Cost (CIC) values in urban core area are higher than previously estimated, so improving the reliability is highly valued. The MV network of Helsinki is almost all cabled (99.7%) [85]. Fast and accurate fault isolation and power restoration are difficult tasks to realize, especially in underground distribution networks with a lot of interconnections. To further increase the benefit of DA, intelligent solutions to support fault management have been selected as future smart grid methods to improve reliability in Helsinki [85]. Helen Electricity Network Ltd. has together with Aalto University and Tekla Corporation researched and developed self-healing methods and schemes to be deployed in the distribution management system of Helen.

DMS of Helsinki has a powerful engine for geospatial data management and applications to facilitate network operation. The system is also incorporated into DSO´s other business processes, e.g. outage communication. It provides tools and automation to monitor and control the electricity distribution network efficiently. The network data in the NIS is the core of all applications in DMS. The DMS also interoperates with SCADA allowing real-time data monitoring and control, thus making an effective platform for self-healing FLISR solutions for urban distribution networks.

The enhanced model was designed and tested with Tekla DMS in 2014, since Tekla DMS is the auxiliary tool of network operation in Helsinki [85]. The new FLISR program was tested with the whole MV network of Helsinki.

The centralized solution is employed in this project. Demonstrated fault management steps are displayed in *section 3.4.1*. Protection detects a fault in the network, breaker opens and an interruption begins. Also, the DMS collects the information from the automated secondary substations. Based on network topology and the collected FPI signals, the FLISR program understands that a fault has passed the switch connecting the second distribution substation and the interconnected line to right. Collected active FPI information is displayed on the DMS. No other active fault indications are encountered. Afterwards, the Tekla DMS executes the actions one to six described in *section 3.4.1*. Based on these actions, a switching sequence is generated. Hence, the switching sequence is implemented in practice, the faulty line section is isolated and the supply is restored.

According to [85] the program is still under demonstrative and testing phase. Next target is to research and develop the model and the FLISR functions more for the desirable features for automatic fault management in city networks, to create the so called CITY-FLISR solution. The final target is implementing the CITY-FLISR solution to the present rural FLISR solution so that the next level FLISR is able to handle fault situation not only in rural distribution networks, but also in urban distribution networks. It should be noted that even though the operating principles differ in many respects, the implementation of a self-healing FLISR solution for urban distribution networks can be based on the same concept as the FLISR solution in rural networks [85].

5.3 Case study 3

Fortum is a leading electricity distribution company in Northern Europe. It operates and manages regional and distribution grids in Finland, Sweden, Norway and Estonia, giving service to approximately 1.6 million customers. Fortum is a growing company constantly developing future energy solutions and focuses on investing in network maintenance and automation, further improving reliability and quality of the supply of electricity to its customers.

The target of this specific pilot project was to verify the functionality of the automatic FDIR concept. The pilot project is divided into two phases. In the first phase, 4 new line disconnectors and 2 new reclosers were incorporated into the distribution network and substation level distributed intelligence into the primary substation. The disconnectors are equipped with current sensors, which can support fault location indication to the DMS 600, in order to determine accurate fault locations. The devices are equipped with current sensors, which can supply data for the substation system and for the distribution management system, for determining fault locations. Locations of the new devices were selected based on feasibility calculations made with Luova reliability analysis tool (ABB´s reliability analysis software) and on the basis of historical fault data. [150]

Additionally, the substation protection equipment was renewed using IEC 61850 compliant 615 protection relays of the ABB Relion product family to provide improved protection and fault distance calculation capabilities, especially for earth faults. The replaced static protection relays that initiated in the 1970´s were not able to accomplish the new requirements when it comes to fault data recording, modern TCP/IP communication and earth-fault protection. [150]

In the system illustrated in *Figure 5-1*, control and automation functions can be found at both local, substation and control center levels. A system that keeps track of the existing loads at various locations and supply capability of alternative network configurations supports fast implementation, fully automatic fault location, fault isolation, network reconfiguration and power restoration functionality, i.e. the creation of a self-healing power distribution network. The latest advance has made it possible to locate some functionality also to the substation level.

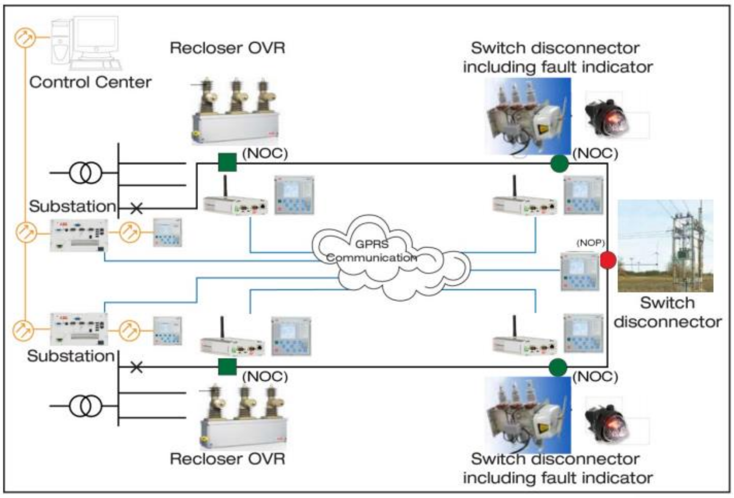

Figure 5-1: Automation functionality at different locations in a distribution network using a combined approach [150]

MicroSCADA Pro DMS 600

MicroSCADA Pro DMS 600 is a distribution network management system (DMS), which is able to extend traditional SCADA competences by providing geographically based network views and advanced distribution management functions over the entire medium voltage network. DMS 600 integrates static information stored in the network database (NIS) with real-time process data acquired through the SCADA system. DMS 600 features tools for comprehensive network topology management providing maintenance of switching status data, connectivity analysis and topology representation via feeder coloring, rapid and precise fault location, analysis and advanced outage planning, which essentially reduces outage duration.

Automatic Fault Detection, Isolation and Restoration (FDIR)

In the first phase of the pilot project, the DMS had a central role in order to provide the FLISR functionality. DMS enabled accurate and reliable information regarding the network situation. When a switching sequence was created, information about network loads, open connections, occasional earthings, ongoing construction work, etc. had to be considered. Solutions in networks including DER and demanding data maintenance concerns are somewhat easier to handle in a reliable and dependable way in the centralized DMS system.

In the second phase of the pilot, though, the feasibility of running the FDIR functionality in the substation system (COM600) is verified. With this decentralized DMS/FDIR approach the central system is not required to be directly involved in the process related to a specific substation. The feasibility of such solution depends on the capabilities of the selected systems as such and their ability to work together [150].

The DMS gives information on both the number of outages and their duration.The operation sequence of the FDIR functionality incorporated in the DMS system follows that the distributed intelligence in the substation serves the DMS with a fault report. The SCADA system delivers to the DMS system the position indication of the disconnectors and recloser, also including the status of possible fault indicators. Then, the DMS system locates the fault and creates a switching sequence for isolation of the fault and for restoration of the power supply to make use of alternative supply routes (back feed). The switching sequence is sent to the SCADA system for fulfillment and the SCADA puts it automatically into practice. This is done step by step so that the sequence does not proceed to the next stage until the site indication has been received from the switching device. Tripping of a breaker during the sequence will stop the sequence.

The communication means for the project uses the public network (GPRS) for the network automation devices via IEC 60870-5-104 communication with the SCADA system, which cooperates with the DMS system. The substation level distributed intelligence (running on the COM600 grid automation controller) and the substation RTU communicate with the control center by means of a private fiber optic TCP/IP network.

Lastly, in the fault management process the following levels of the distribution network take place:

- ***Bay level in the substation:*** modern protection and control relays offer versatile protection algorithms for earth fault detection. The protection functions allow fast and selective protection. The start signals of protection functions are triggered into a disturbance data recording using the COMTRADE format. The data recording admit prediction of non-permanent earth faults in the network. Furthermore, the recordings include status indications of the circuit breaker and auto-reclosings based on the events.

- ***Protection zone level:*** the reclosers in the line feeder enable automatic isolation of the fault into the dedicated protection isolation zone. The status indications of the circuit breaker and the auto-reclosings are directed to the upper level. The disconnectors equipped with fault indicators are able to transmit status indications and measurement data from the fault indicators.
- ***Distributed intelligence in the substation:*** disturbance data recordings are stored in a grid automation controller. The controller calculates distance estimations of network faults immediately after a fault situation (semi-online). The grid automation controller creates a fault report containing the distance estimation information and sends it to the DMS.

The results and considerations learnt from this project are described in *Table 5-1*. As it was mentioned in other practical experiences of the self-healing concept, this pilot case had also the target of improving the reliability of the electricity distribution network as well as to significantly enhance the power quality experienced by the customers located among the concerned feeders in the Kirkkonummi area. Major driving factors for the investment were, on one hand, strengthening the Finnish regulatory influence, and, on the other hand, the necessity to shorten and improve fault location times, reliability and accuracy, especially for earth faults [150].

Table 5-1. Effects of the pilot case on the reliability of the distribution network

Function	Decrease of SAIFI	Decrease of SAIDI	Comments
New protection zone	30-40%	20-30%	Downstream faults not affected
Fault location	-	50-60%	Trial connections can be omitted
Fault forecasting	20%	-	Permanent fault probability reduced

5.4 Case study 4

In order to minimize the fault outage time, the Dutch DNO Stedin has started a project to bring in automation to its distribution network. The first phase of the project resides on installing intelligent FPIs, while the next two phases use more advanced techniques such as remote-controlled Ring Main Units (RMUs) and a completely self-healing distribution feeder.

In the Netherlands, the distribution network consists of underground cables, which means permanent faults may occur that cannot be solved by stand-alone automatic reclosers. Stedin developed a self-healing network pilot based on a software restoration routine that employs several RTUs [117]. The RTUs communicate through a General Packet Radio Service (GPRS) network to identify the fault location, isolate and restore supplies in steps automatically.

Automatic FLISR schemes can be realized with diverse architectures, as it was exhibited in section 4. A fully centralized architecture uses a distribution a DMS that has a whole picture of the network topology. Local, centralized architecture uses intelligent master controllers that communicate with a limited number of dependent devices.

The architecture installed by Stedin is fully decentralized, where the intelligence is distributed between several nodes. The FLISR algorithm operates the messages delivered by the RTUs. Thus, the communications architecture mirrors the electrical network, which makes it easy to add and remove nodes.

For the Stedin self-healing distribution network pilot, a medium-voltage (23kV) network in Rotterdam´s city center was designated. This network involves 33 23kV secondary substations interconnected in an underground cable ring operated as two radial feeders by creating a normal open point [117]. This is shown in

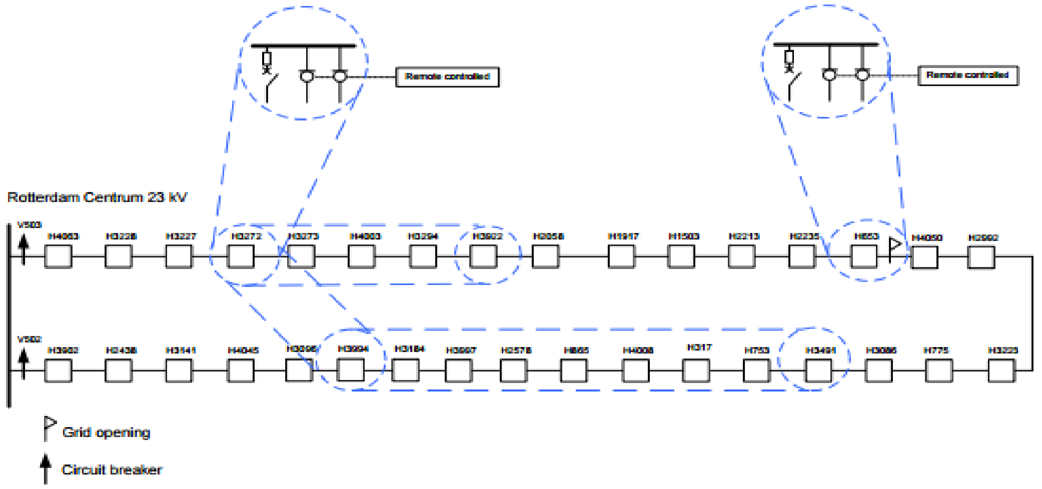

Figure 5-2: MV-network for the self-healing grid pilot project [117]

Ideally, all 33 secondary substations would be fitted with automatic switchgear, but this is an exceedingly expensive option. The cost-effective solution was to select five secondary substations and divide the ring into two feeders, each with three sections and each with approximately equal cable length and number of connected customers.

The five secondary substations all are equipped with the following distribution automation equipment: 1) motor drive to operate the load break switches, 2) RTU in which the logic is programmed, 3) fault passage indicators, 4) voltage presence detection, 5) the circuit breakers. These are 23kV circuit breakers located in the primary substation and they are equipped with a protection relay to trip the circuit breaker, supervisory control and data acquisition RTU for monitoring and control and self-healing RTU and a smart controller to start the FDIR sequence and reclose the breaker.

The self-healing cabinet box is equipped with the RTU that contains a battery and a GPRS modem for communication purposes. The fault passage status is calculated within the RTU by means of current measurement on the input and output cables. Additionally, a voltage presence indicator is connected via capacitors to each cable to detect whether the cable is energized.

The Stedin self-healing project was undertaken in cooperation with Schneider Electric, designer of the T200i platform [117]. For this pilot project, the T200i RTU was installed in Stedin´s self-healing network. Schneider Electric also developed the software needed to create the self-healing algorithm that runs on the RTUs.

Fault Location and Isolation Algorithm

Regarding the sequence that the fault location and isolation algorithm follows is first started when a controller at the primary substation source detects operation of the protection relay. The algorithm functioning is based on two phases. Phase 1 is the upstream isolation phase: each node analyzes whether the fault is located upstream of itself and, if needed, isolates it. Phase 2 is the downstream isolation phase: each node analyzes whether the fault is located downstream of itself and, if required, isolates it.

During phase 1, messages are sent downstream from the feeder circuit node, going from the breaking node to the making node. A message is received in each node and subsequently its correspondingly fault-passage indicator is analyzed in order to find out whether the fault is upstream of itself. If so, on its switches will be opened to isolate itself from the fault.

During phase 2, messages are sent upstream from the making node to the breaking nodes and back to the feeder´s circuit breaker making node. During this phase, each breaking node will complete its analysis of whether the fault is downstream of itself. If so, a switch will open to isolate on the upstream side of the fault.

Regardless of previous mentioned and phases involved, the algorithm also has to consider other features:

- Safety: when any node is put in local mode, the self-healing scheme is automatically disabled at all the other nodes
- Robustness: if a switch fails to isolate a fault, then the system will try the next switch
- Fault tolerance: this is the ability to handle missing fault-passage indications.

Communication Infrastructure

Stedin has structured their own communication infrastructure. For primary substations and own TCP/IP network consisting of fiber optic and copper was designed. For the secondary substations, GPRS/UMTS are used from a selected telecom provider. [92]

For this pilot case the communication between the RTUs of the self-healing grid occurs via GPRS network while the communication to the circuit breakers in Rotterdam Centrum substation and the EMS takes place by means of fiber optic network.

Started in October 2011, Stedin´s self-healing network pilot project was finalized and fully commissioned in June 2012. Since the self-healing network has been in service, no faults have taken place on this automated feeder network. [117] The GPRS communications system used for the project was designed as a telephone network that can be also used to transfer data. Yet, the system gives quality of service to phone calls, which can affect the availability of the communications network for self-healing applications negatively. Also, as an energy-saving practice, the telecom provider turns off some antenna sites at night, which may impact signal reception at some automated substations. These issues need to be addressed during the planning phase of the communications infrastructure for the self-healing grids. Additionally, most of the interruption of the self-healing network is caused by the modem reset invoked by the telecom provider. The telecom provider is responsible of resetting all unused connections daily, which results in a restart of the RTU modems. During this reset, the self-healing network is unavailable for two minutes.

Future developments are currently taking place. Stedin has started a second self-healing network project that is not based on a fully decentralized architecture but on a regional controller placed in the primary substation source with a number of local control units located in the secondary substations. Further, the GPRS network is used for communication between the regional controller and the local control units.

The regional controller is the core component of this system. This is where the self-algorithm runs and where all the restoration switching decisions happen. The local control units execute these switching actions and provide the regional control unit with an actual process image of the network status.

Stedin has also started the implementation of a DMS in its control center. This system can be equipped with self-healing algorithms, and Stedin plans to explore all of the functional features of such system.

All projects are subject to a 12-month trial period, after which all projects will be evaluated. Stedin will then be well forced to decide on the design of future distribution networks, the self-healing algorithms required and the new technologies to be installed to improve the reliability of supply. [119]

5.5 Case study 5

A pilot distribution automation project was initiated by Dubai Electricity and Water Authority (DEWA) in 2010 for MV network. This pilot project included 38 secondary distribution substations (11/0.4 kV) connected in open ring topology with three radial feeders and two NOP to be operated as radial feeder in a ring configuration for reliability purposes as illustrated in *Figure 5-3* [89].

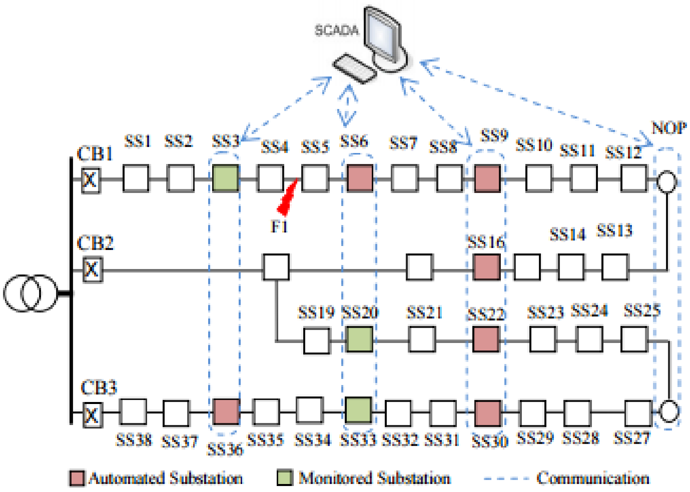

Figure 5-3: Selected MV network for DEWA pilot DA Project **[89]**

The cost-effective approach to minimize customer minutes lost and reduce outage duration was implemented by dividing each feeder into three sections employing automated substation. Monitored substations with fault passage indicators (FPIs) were deployed in the middle of long sections in order to reduce fault localization time. The existing substations were modernized and equipped with smart distribution automation including: 1) RTU controller and GPRS modem, 2) fault passage indicators, 3) voltage presence sensor (or voltage monitoring relay), 4) motorized actuator for the ring main unit (RMU), 5) UPS system with backup batteries and 6) modbus power quality meter in selected substation.

Other substations were also selected for remote monitoring of FPI in order to attain a better fault localization. Monitored substations have the similar system of automated substation except for the motorized actuator used to enable flexibility and scalability in case of ring reconfiguration.

The self-healing concept is realized in a centralized approach via DMS and SCADA system. The communication protocol sustained by DMS is IEC 60870-5-104 over GPRS.

This pilot project was evaluated based on two parameters, percentage of power restored using automated substations and reduction in service restoration time. *Table 5-2* illustrates the percentage power restored based on different simulated fault scenarios performed in each feeder section. The fault scenario in first feeder section (F1) is demonstrated in *Figure 5-3* above.

Table 5-2. Percentage power restored based upon different fault scenarios [66]

Feeder CB tripped	Fault Scenario	Simulated Fault Location	% Power (kVA) restored in 2 minutes using DA
CB1	F1	SS4-SS5	48%
CB1	F2	SS7-SS8	52%
CB1	F3	SS10-SS11	46%
CB2	F4	SS13-SS14	54%
CB2	F5	SS19-SS20	78%
CB2	F6	SS24-SS25	50%
CB3	F7	SS28-SS29	72%
CB3	F8	SS32-SS31	52%
CB3	F9	SS36-SS37	75%

From the result, it can be concluded that in average 59% of interrupted power was restored within two minutes by means of the DA solution. In addition, around 40 % customer minutes lost (CML) improvement was achieved for the examined MV ring pilot case study.

5.6 Lessons learnt from case studies

A total of 20 case studies have been studied, out of which 5 have been carefully detailed with the purpose of showing the practicality of the research and thus of learning from past projects by bringing together any lessons learnt and the effect they had. The key lessons have been summarized in the following points:

- Utilities found that communications networks require greater resilience than power delivery systems because they must be able to control automated switches under conditions where the grid system is damaged or not properly functioning properly due to faults, downed lines or other grid disturbances
- Utilities with legacy communication networks should conduct evaluations and implement upgrades before deploying FLISR technologies and systems
- In general, for future deployments of smart grid applications, greater attention has to be put into the performance of the telecom network. Utilities should anticipate to the telecom providers and adapt the performance of these types of networks by for example introducing different data contracts to make the network suitable for these types of applications
- Deployments of FLISR technologies and systems required additional steps and considerations that do not necessarily follow traditional utility asset management practices. Because automated devices often require more frequent firmware and software upgrades as well as customized refinements to meet the unique needs of

various distribution system configurations, more frequent field tests and evaluations are often required

- Continuing maintenance processes and practices are essential for utilities
- Vendors typically play a critical role in implementation and it was often encountered that utilities needed hands-on interactions to customize product and service offerings to meet utility and feeder-specific needs
- Working closely with vendors was necessary for quality assurance. Moreover, commissioning resulted in fewer miscommunications and oversights, and ultimately enabled faster field device interoperability. New procedures for change management and vendor-related communication protocols are helpful for ensuring deployment success
- Education and training programs for headquarters and field staff about the requirements of the new devices and systems is essential. The utilities found implementation of FLISR systems resulted in significant process changes that require greater expertise in information systems, database management, and grid analytics. Further, technical teams of software and hardware engineers, data analysts, and business process specialists were typically required for success.
- Another fact to remark is that not all medium-voltage networks are suitable for self-healing systems. In meshed networks, various possibilities are available to restore the network following a fault. This results in difficulties for the software routines and probability of malfunction increases. Thus, to maximize the benefits of distribution automation, the automation functions should be included in future distribution network design.

6. REVIEW OF THE CONCEPT

The research has reviewed and examined the approaches of automated FLISR as a self-healing function and its implementation within the distribution network. Unfortunately, there is no clear definition in the related literature about the self-healing features and its implementation solutions.

For our system, we have followed the definition of self-healing as the capability that allows a system to observe that it is not operating correctly and, without (or with) human intervention, makes the necessary adjustments to restore itself to normality. Healing systems that need of human intervention or any external agent to the system can be regarded as assisted-healing systems.

The main goal of the self-healing grid is to fully automate the traditional Fault Location, Isolation and Restoration (FLIR) steps which are needed to localize, isolate a fault and restore the grid. If this is done in a fully automated way it can be denoted as automatic FLISR (or self-recovery). If required human intervention is deployed, then it can be referred as a partly automated FLISR. Both are involved within the framework of self-healing. To reach the goal of self-healing, distribution grid automation is applied and communication networks are used to transfer data and commands to various switching devices (circuit breakers, reclosers) with IEDs. The automated capabilities of IEDs, such as measuring, monitoring, control and communication functions make it possible to implement fully automatic FLISR.

FLISR schemes can be implemented following different self-healing solutions or approaches. These can be acknowledged by various names. Fully centralized schemes or only centralized solutions use a Distribution Management System (DMS) that has a complete picture of the network. Local centralized schemes or decentralized or even for some authors substation-based solutions use intelligence at master controllers (based on IEDs) each of which communicates with a limited number of slave devices (RTUs). Last, but not least, fully decentralized architecture or also known as distributed solution. This employs the intelligence distributed between several nodes.

Figure 6-1 demonstrates the sample of a proposed centralized approach. In centralized schemes, the decision relies on the control center. The control center gathers the status information from the local secondary substations via a telemetry system and then sends the command for isolating the faulty section. Commonly communication is realized via GPRS using protocols. Fully automated FLISR requires full automation and the switches of the network to have the capability of being remotely controlled. It may seem reasonable that a cost-effective solution would encompass selective automated secondary substation automation along the network with RTUs and wireless gateways to achieve communication with the control center as shown in *Figure 6-1*. As displayed, centralized solutions require a powerful DMS and distribution SCADA to control the intelligent switching algorithm (referred throughout the work as SHG or FLISR algorithm). The DMS system collects the data from the automated secondary substations, where usually I/O signals are used for fault detection via RTUs, e.g. fault current was detected or not, and subsequently an analysis of the fault indicator data is carried out in order to create the switching sequence to isolate the faulty section. Then the DMS will deliver the switching sequence created by the SCADA to be implemented in practice. Once automatic switching is successfully deployed, the DMS will analyze the network topology again to check that no section remain under outage. Subsequently, in case no disturbances are found, the faulty section can be isolated by remote controlled switches. Manual switching operation may be needed depending on the level of automation.

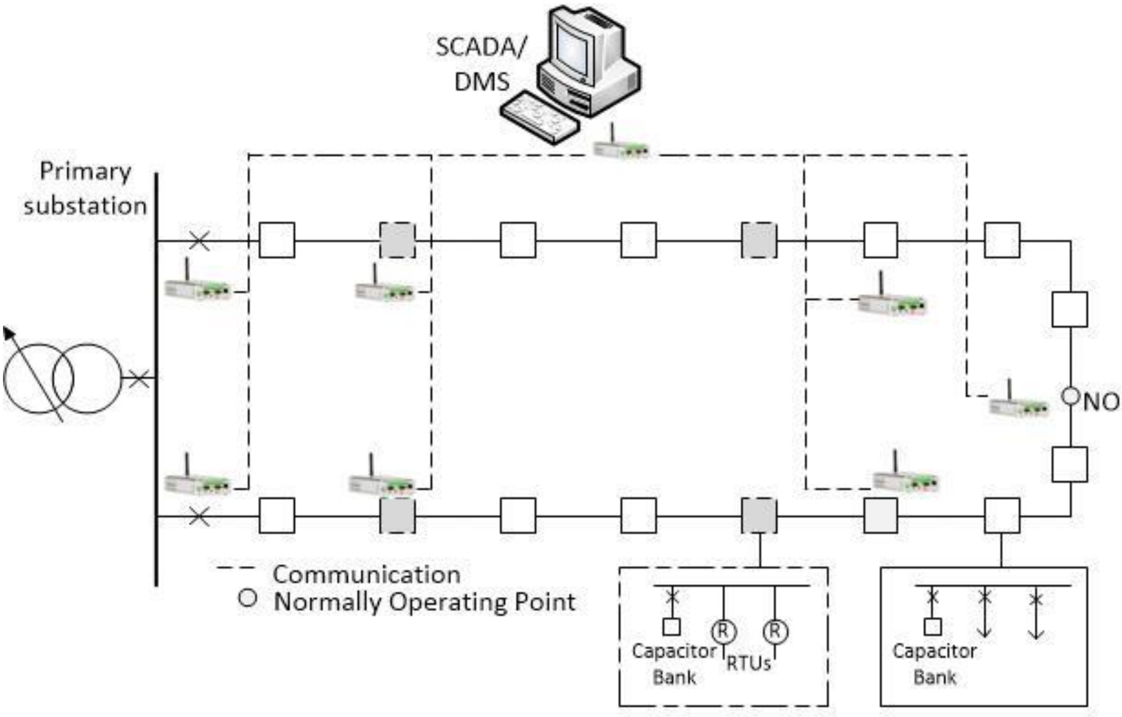

Figure 6-1: Proposed scheme for centralized self-healing architecture

In a centralized architecture, no actions can be taken without the control center knowledge, which is the one that gives maximum operator visibility and is responsible for all network reconfiguration and conditions as it was just explained. In centralized FLISR systems, secure, reliable two-way communication and powerful central processing of data are crucial. Centralized FLISR systems require a fast and reliable communication to operate in addition of accurate load model information due to the fact that each switch controller necessitates communicating with the control center directly. This may lead to latency because the response time of the complete automation system may be relatively high.

On the other hand, in decentralized, substation-based FLISR systems centralized systems, the intelligence is applied at the substation level and communication to the control center is no longer necessitated. As shown in *Figure 6-2*, the SHG algorithm is deployed at the substation device (IED) and hence, the remote monitored I/O terminal modules installed on the feeders have to be connected to the distribution substation device (controller) over communication network via wireless communication such as GPRS. The regional controller or IED obtains information and status indication of the distribution grid by the local control units (remote I/O switches or reclosers mentioned) and when some disturbance occurs the controller will initiate the self-healing algorithm. Upon receiving information of each secondary substation, FLISR algorithm will fulfill the fault isolation process. Thus communication under this approach occurs over short distances which lead to higher speed performance and lowest restoration time as compared to centralized architectures. Consequently, lower bandwidth necessities are required; thus arising in relatively lower costs on the communication side and enhanced efficiency of the operations.

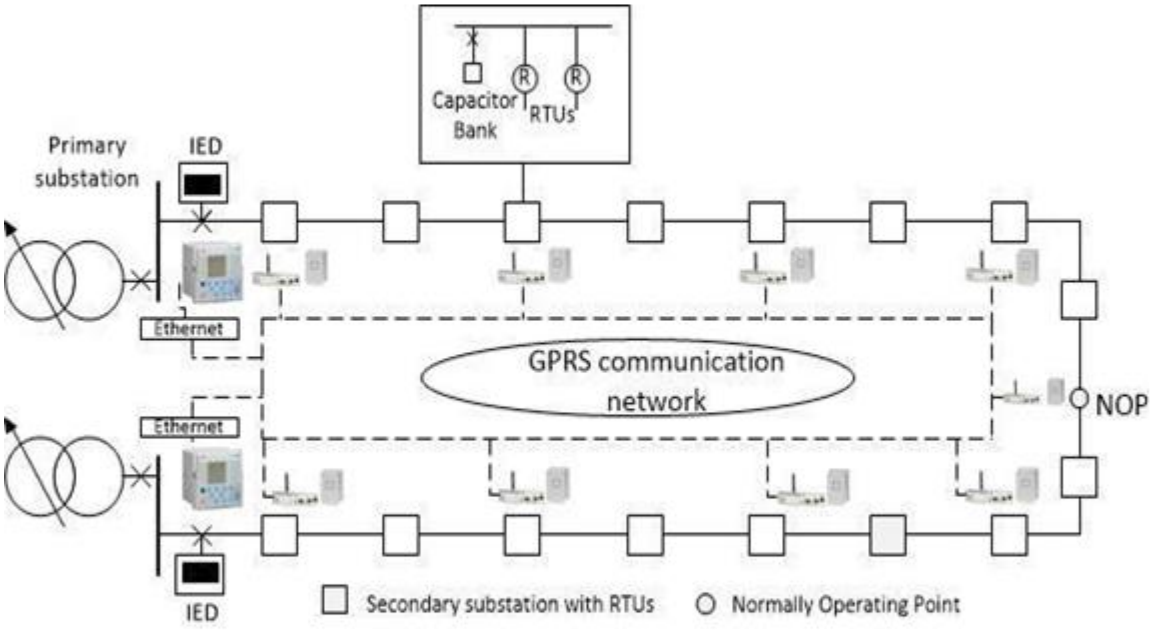

Figure 6-2: Proposed scheme for decentralized self-healing architecture

Differently from previously, *Figure 6-3* shows a proposed scheme for a distributed solution. In this case, distributed approaches or fully decentralized architectures use controlled devices (e.g. IEDs) at each switch or recloser location (secondary substations), where the self-healing algorithm is deployed. Hence, the FLISR algorithm resides on several devices at the feeder level and not at the substation level or control level as for earlier approaches. These devices communicate among each other in order to determine where the fault occurred and to achieve the appropriate switching actions necessary for the restoration process. In the distributed approach no longer monitoring remote terminal I/O units are used but IEDs at each switch location. As displayed in *Figure 6-3*, these controllers are located in selected secondary substations and communicate via a communication network, e.g. using GPRS via IEC 61850 protocol.

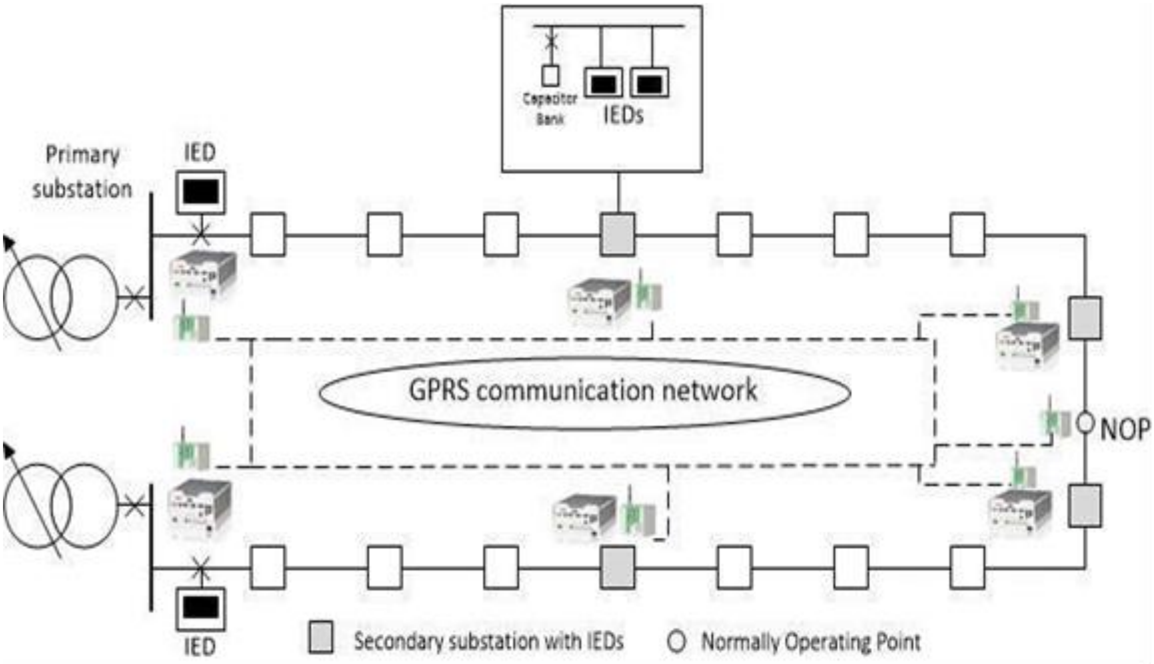

Figure 6-3: Proposed scheme for distributed self-healing architecture

Again, the ideal solution is the employment of control units at each secondary substation, but a cost-effective strategy is the one to be perceived. Hence, dividing the network by selective controllers in a number of feeders with approximate equal cable length and number of connected feeders may be an optimized option attending to cost-benefit purposes. This scheme is also referred as fully decentralized since the intelligence is distributed between several nodes without the need of DMS. In view of that, in this case the reliability of this approach is greater in comparison with other approaches as the switching decision (intelligent devices) are distributed over a number of master substations rather than centralized in the control center. This solution may not be able to operate under non-standard network topology and is unable to operate with multiple faults. However, FLISR systems with distributed intelligence and mesh networking are the simplest to configure and fastest to implement as they can be directly integrated into the SCADA.

Even though SCADA is not necessary to govern distributed intelligence systems as it has been mentioned, this is perfectly compatible with the SCADA. Along with this, if DMS is used, implementing a distributed-intelligence in conjunction with the control center is referred as a combined solution, which is shown *Figure 6-4*. The operation sequence of the FLISR functionality incorporated in the DMS system follows that the distributed intelligence in the substation serves the DMS with a fault report. The DMS processes the fault report; it locates the fault and creates the required switching sequence for isolation of the fault and the restoration of the power supply. The switching sequence is sent to the

SCADA system for fulfillment which is the one that puts it automatically into practice. Typically implementation is to locate a master substation at the primary substation and communicate over radio or GPRS with the automation devices on the feeder (via protocols). Communication from the substation RTU (master controller) with the control center can be accomplished via the public network GPRS or by fiber optic in case it is already available at the primary substation. In this case operation may not be reported to control center in case a failure in communication process between the control center and master station exists; thus operator visibility is limited and may suffer single point of failure as in centralized systems. If the main substation control communication fails, the entire system is down.

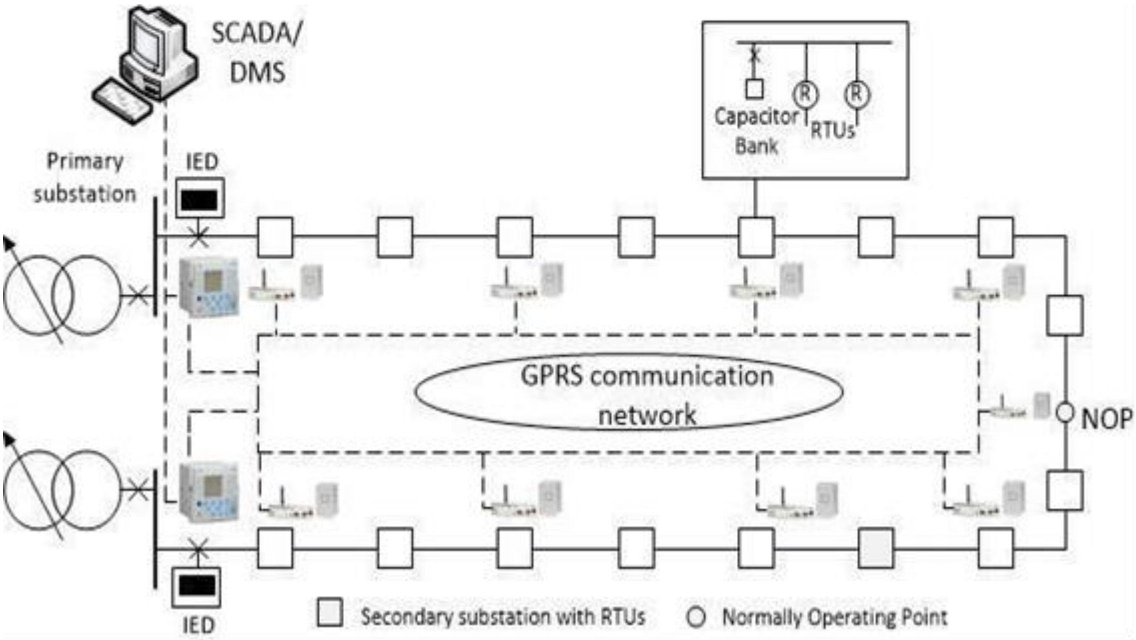

Figure 6-4: Proposed architecture for combined self-healing architecture

In summary, it could be said that FLISR systems can use either centralized intelligence where the majority of the decision capability falls within the NCC or decentralized (including fully decentralized) intelligence architecture where the decision capabilities for automation fall within the secondary substation with monitoring and limited control for the NCC. Under centralized control, primary and secondary substation data and all feeder switch status are informed over the communication network to the centralized control system. The main advantage of the centralized control is that all distribution network data is stored locally at the control center and updated on a real-time basis. In this way, the control system has a full view of the network condition before and after the fault. Thus, load transfer can be done in optimal way either for planned or unplanned faulty feeder isolation. The major disadvantage of centralized control is the excessive amount of data that should be communicated and stored in real-time even during the times when the net-work is working normally. Conversely, decentralized control transfers the responsibilities of managing the faults from the centralized control center to intelligent controllers located at the feeders and substations. Using decentralized control methods present two main ad-vantages:

- Their simplicity and fast operation
- They can be deployed locally to the less reliable zones of the network, and then the system can be gradually expanded to other feeder sections.

Systems using decentralized (and fully decentralized) intelligence can be combined with centralized solutions, and present the advantage of having the capability to remain under operation in case communication failure from devices on the network to the control center exists. Along with this, distributed intelligence systems enable local switching decision without the need of continually having to communicate and transmit data to the control center, and thus response times can be attained quicker (no need to wait for instructions).

6.1 Distribution generation and demand response impact on self-healing functionality

The increase of DG may result on several problems on the feeder. Distributed generators are seen as a possible source of fault current that even if considered small compared to the level of fault current from the electric utility´s generators, can be big enough as to trigger faulted circuit indicators that are downstream (further from the bus station) of the real fault. As a consequence, the incorrect feeder segment will be recognized as faulted, and restoration switching actions may reenergize the fault and lock out numerous feeders. This can be solved by using directional fault current indicators that detect the direction flow of the current. Centralized approaches that take into account full view of the network and thus account for short circuit contributions from distribution generators may reduce this trouble.

Another challenge that results from the presence of distributed generators is that related to the load. As explained, fault location and system restoration (FLISR) systems constantly monitor the power flowing into and out of each feeder section in order to determine the load that may be needed to be transferred in case of short circuit occurrence. The problem comes when the distributed unit trips off the line after the fault occurs. As the unit is not allowed to reconnect until several minutes has passed following restoration of the normal primary voltage on the electric utility lines, the amount of load to transfer may exceed the amount measured previously to the fault. In this case, overloading of the backup feeder will happen. Monitoring distributed generators continuously and taking into account the generation dropping off line when an outage occurs is necessary to overcome this problem and the use of IEDs may be one possible solution. However, for larger utility scale DG this may be difficult and result particularly expensive.

Another fact that should be remarked is that theoretically in a DG system, when a fault occurs at the end of the feeder, the fault current consists of the contribution of (1) fault current from the utility network, *I1*, and (2) fault current from the local generation, *I2*, as shown in *Figure 6-5*. The impedance at the lower level of the feeder is enlarged with the addition of the DG, thus fault current from the utility network *I1* is diminished. Nonetheless, fault-current contribution from the local generation *I2* is added.

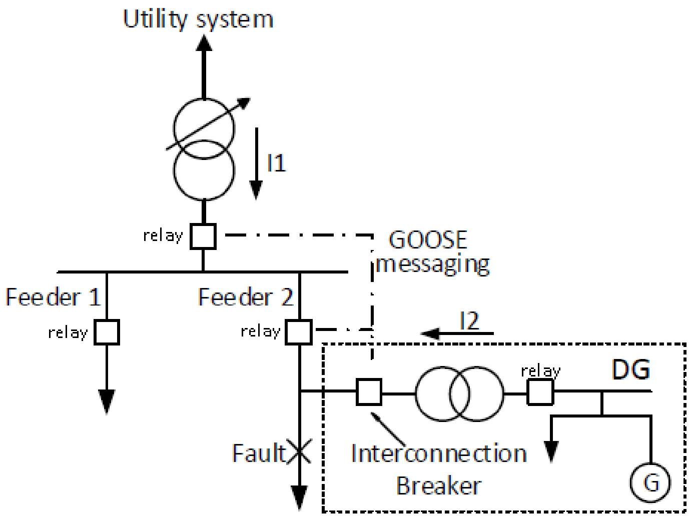

Figure 6-5: Fault current contribution in a DG system

If a significant amount of DG is connected to a MV network, the fault current perceived by the feeder protection unit can be reduced, resulting in improper or non-operation of the relay or Intelligent Electronic Device (IED). Along with this, new communication technologies, such as IEC 61850, bring important advantages for the information sharing between IEDs, feeder relays and DG protection devices. As the relays are now IEC 61850-capable, the interoperability issues between the relays from different vendors is decreased. IEC 61850-capable IEDs are able to communicate using Generic Object Oriented Substation Event (GOOSE) messages, hence excluding the necessity to require multiple communication protocols. Through GOOSE messages, the feeder relays could obtain information from the interconnection IEDs on DG disconnection and establish the settings and parameter by switching the protection setting group. One possible solution for the restoration of the local loads if the distributed generation does not comply with the loading conditions is a setup with a tie breaker or normally open point (NOP) as shown in *Figure 6-6* below.

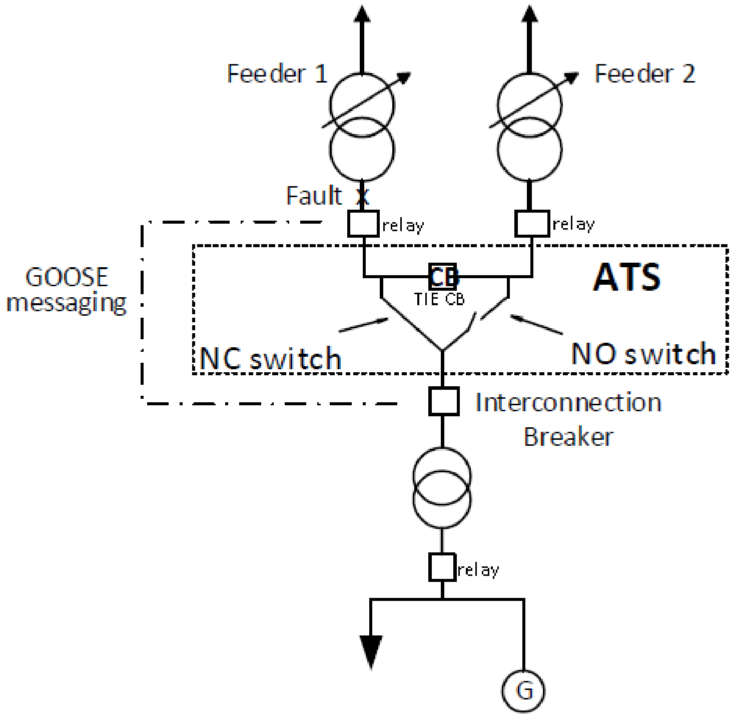

Figure 6-6: DG architecture with ATS via GOOSE messaging

For the case of two sources of the grid being present, the DG is always connected to only one. In case one source is lost, the DG is transferred to the backup source on the network in order to restore all the loads. This is accomplished using an Automatic Transfer Switch (ATS) controller. The substation relay will detect an overcurrent and trip the substation breaker (CB1). Communication via GOOSE messaging to the rest of relays (i.e interconnection relay) will now take place in order to perform the transfer to the backup feeder (feeder 2) for temporary restoration, and then, perform a transfer back to the main feeder.

Regardless of previous mentioned troubles on which DG may negatively influence on network systems, the presence of distribution generation and other distributed energy resource (i.e. storage) can offer opportunities to the performance of self-healing systems. In cases where FLISR load transfer to backup sources are blocked due to the high load, FLISR systems may make use and exploit distributed resources such as generation and storage aiming to reduce the net load being transferred.

Distributed generation promotes the development and would enable greater utilization of microgrids. A microgrid concentrates a localized grouping of electricity generations, energy storages, and loads, connected to a traditional power grid (macrogrid) in the normal operation state. The users in a microgrid are capable of producing low voltage electricity utilizing distribution generation, such as photovoltaic installations, wind turbines, fuel cells, and other resources. The point of common coupling with the macrogrid can be disconnected, with the microgrid operating autonomously. This operation will turn into an islanding microgrid, in which distributed generators continue to generate power to the users in this microgrid without obtaining power from the electric utility sited in the macrogrid.

That cluster of power can be used in many ways. Sensing a voltage drop in a specific power sector, the microgrid can be configured to uphold service to critical customers (e.g. hospitals or emergency services). Thus, the multiple distributed generator resources and the ability to isolate the microgrid from a lager network in a disturbance state will provide highly reliable electricity supply.

In this light, in order to realize self-healing strategies during outages, microgrids can be switched to the islanding mode above explained and as a result the users in microgrids will not be affected at all during outages. Besides, FLISR applications may use microgrids to restore faulted feeders due to lack of available capacity on the backup source. This is because electric distribution facilities are regularly loaded to more half of their rated capacity and sufficient capacity may not be available on back up sources when required. In the same way, demand response can be used to release some existing capacity.

Similar to self-healing, the ability to cope with the network management efficiently by fast-routing/rerouting and auto-bandwidth to maintain a dynamic network configuration based on real-time interactions with available data and intelligence is crucial for providing fast response to the demand and for avoiding grid instability. As explained, demand response programs help to succeed in peak electric demand reductions, lower consumer energy bills, stabilize the power system, and also reduce power shortages. Through demand response programs sensors are able to recognize peak load problems and utilize automatic switching to avert or reduce power in strategic places, removing the chance of overload and the result in power outage. The meters may act as sensors that can trigger an alarm that the power is out. Also, reducing electricity demand at critical times (e.g. when a generator or a transmission line unexpectedly fails) by demand response actions can also help return electric system reserves to pre-contingency levels.

Demand response and electric storage are necessary for addressing economics of the grid and are expected to support reliability by mitigating peak demand and load variability. Electric transportation is considered helpful in meeting environmental targets and also has the potential to mitigate load variability. Balancing the range of the characteristics of these resource types presents challenges in keeping reliability and requires a quantum leap in harnessing communication and information technologies.

Last to mention is that as it was stated along this chapter, self-healing main characteristics involve self-prevention and self-recovery. Automatic fault detection, isolation and restoration of power supply in response to a disturbance or fault covers the self-recovery part. Self-prevention has to with the real-time performance and continuous optimization of the power system in its normal operation state. As such, demand side management and demand response in addition to being a key integral part of the smart grids, they can be considered critical technologies of self-healing distribution grid which come into play on the self-prevention part. Demand-side management includes saving energy, optimizing resource allocation and guaranteeing security of electricity increasing end-user electricity efficiency and optimizing power consumption. Demand response has to do with the power market users' response according to the market price or incentive mechanism. This changes the normal power consumption mode of market participation. In the same way, microgrids are able to lighten the peak pressure of power supply to realize the electricity peak load shifting, optimize and enhance energy efficiency for the purpose of self-healing control of distribution network.

7. CONCLUSIONS

The power distribution system is an essential part of the electric power system in order to provide reliable, efficient and safe power to consumers. This, in conjunction with the modernization of the power distribution grid has prompted the implementation of self-healing functions, particularly self-recovery or automatic FLISR for improving reliability, power quality and increasing operations efficiency. With deployment of these distribution automation applications electric distribution utilities cannot only achieve these performance goals but also enhance situational awareness and even reduce the financial penalties they may incur due to system outages. Self-healing nature of the smart grids through the implementation of distribution automation applications as it the case of automatic fault location, isolation and service restoration has been presented as a an effective solution with the purpose of automatically removing faults or disturbances from the distribution network, and presents a broad number of benefits. Hence significant reliability improvement of various reliability indices can be achieved. Reduction of “energy not supplied” and fault investigation time as well as providing “premium quality of service” are other functional benefits. In addition, monetary benefits can also be attained. Some of these involve, increased revenue (sell more energy), reduction of customer cost per out-age, additional revenue from “premium quality” customers, labor/vehicle savings, etc.

A self-healing smarter grid is able to provide with a number of benefits that lead to a more stable and efficient system. Three of its primary functions involve real-time monitoring and reaction, which gives the system the ability to constantly adjust itself to an optimal state; anticipation, which allows the system to isolate parts of the network that experience failure from the rest of the system. In this way, it is possible to avoid the spread of disruption of service while enabling a quick restoration. As a result of these functions, a self-healing smart grid is able to detect abnormal signals, make adaptive reconfigurations and isolate disturbances, eradicating or minimizing electrical disturbances during storms or other catastrophes. And even further, due to the fact that the system is self-healing, it owns an end-to-end reliance that is able to detect and override human errors that may result in power outages. Along with this, because the system severely relies on automation and communication measures, all actions taken by the self-healing grid have to be fulfilled in a safe and sound manner. Personal as well as environmental safety is of greatest importance. In view of that, local control units of all automated secondary substation should be equipped (not all of them comprise of safety features) with a local or remote switch. In the event that a maintenance engineer needs to take actions at an automated secondary substation, the local or remote switching must be put on local mode. As a result no unexpected switching actions can occur.

There are several types of self-healing solutions which can be differentiated between centralized and decentralized intelligence solutions. Decentralized intelligence solutions can be divided into local centralized and fully decentralized solutions (distributed), where the difference remains on level of intelligence. While local centralized, decentralized or sub-station-based solution relies on a single automation device or regional controller for the whole substation, fully decentralized harnesses the intelligence distributed along the net-work by means of controllers at each switch or recloser location. These are referred as distributed self-healing approaches. If a combination of centralized and decentralized intelligence takes place, this is categorized as a combined type architecture. However, there is no one type or ideal solution which fits all possible situations. Thereupon, a careful analysis should be carried out in order to determine which option offers the most appropriate solution. Implementation of a decentralized self-healing strategy may help to solve many of today´s utility challenges, however adding communication equipment and substation control can result extremely costly if not already available at the substation. Deployment of centralized self-healing capabilities to maximize distribution network reliability requires automation of switching points as well as a communication platform such as fiber optic or wireless radios. Further, hardware and software capabilities need to be extended. Distribution of master controllers through the feeders can result prohibitively expensive in case of fully distributed intelligence schemes. Along with this, the best solutions are those that allow the user to cost-effectively automate existing switches or in-stall new reclosers enabling real-time automated decision making in order to enhance operation capabilities at the edge of the grid.

Based on the recent literature and more specifically on the case studies examined, it can be concluded that smart grid solutions not only have an impact on the behavior of the network, but it also affects people which encounter the changing behavior of the grid. In case of a self-healing grid, maintenance engineers and operators of the control center have to adapt fault handling and restoration procedures that have been used for more than thirty years. For gaining confidence and experience in the solution key issues of safety, active participation in the solution need to be treated in early states of the project, and generally a test environment is completed. Moreover, the technologies and systems for successful FLISR operations have different features and operating characteristics than traditional electric distribution assets. Communication networks and software for control and system management often require more frequent maintenance and are subjected to regular upgrades. These features necessitate utilities to evaluate existing business processes and practices; increase training for grid operators, engineers, and technicians; and implement new procedures for cybersecurity protections.

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