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An Enhanced Self-Healing Protection System in Smart Grid: Using Advanced and Intelligent Devices and Applying Hierarchical Routing in Sensor Network Technique

Mohamed Eid Aljahani
Western Michigan University, mohamed.e.aljahani@gmail.com

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AN ENHANCED SELF-HEALING PROTECTION SYSTEM IN SMART GRID:
USING ADVANCED AND INTELLIGENT DEVICES AND APPLYING
HIERARCHICAL ROUTING IN SENSOR NETWORK TECHNIQUE

by

Mohamed Eid Aljahani

A thesis submitted to the Graduate College
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Thesis Committee:

Ikhlas Abdel-Qader, Ph.D., Chair
Johnson Asumadu, Ph.D.
Azim Houshyar, Ph.D.
AN ENHANCED SELF-HEALING PROTECTION SYSTEM IN SMART GRID:
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Mohamed Eid Aljahani, M.S.E.
Western Michigan University, 2014

This paper presents a self-healing protection systems were designed using PSCAD software to test and investigate the efficiency of this method. The system was applied on a typical distribution system with loads, buses, and power sources. The availability of advanced and intelligent devices, such as IEDs and PMUs was the trigger to design proficient and accurate self-healing protection systems which are associated with future smart grids. Deploying optimal sensors distributed within the grid could be a suitable method to monitor and control the distribution network. By using a hierarchical clustering communication technique, optimal sensors can work wirelessly and efficiently without interruption during outages. Also, by using this intelligent and automated method in a smart grid, the duration of outages can be reduced by locating faults and limiting affected areas, which facilitates the fault clearing from the grid rapidly. Also, the proposed system of self-healing protection was simulated using PSCAD software to test the ability of the system to achieve our research goals. The system, as presented in the simulation results, worked smoothly, and successfully showed that the self-healing protection system could monitor and control the grid during outages to locate the fault, isolate the affected area and restore electricity to the unaffected area.
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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>HV</td>
<td>High voltage</td>
</tr>
<tr>
<td>LV</td>
<td>Low voltage</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory control and data acquisition</td>
</tr>
<tr>
<td>VT</td>
<td>Voltage transformers</td>
</tr>
<tr>
<td>CT</td>
<td>Current transformers</td>
</tr>
<tr>
<td>PMUs</td>
<td>Phasor measurement units</td>
</tr>
<tr>
<td>IEDs</td>
<td>Intelligent electronic device</td>
</tr>
<tr>
<td>WAMPC</td>
<td>Wide area monitoring, protection and control</td>
</tr>
<tr>
<td>GPS</td>
<td>Global positioning system</td>
</tr>
<tr>
<td>AMI</td>
<td>Advanced Metering Information</td>
</tr>
<tr>
<td>NOP</td>
<td>Normally open point</td>
</tr>
<tr>
<td>RTU</td>
<td>Remote terminal unit</td>
</tr>
<tr>
<td>RMU</td>
<td>Ring main unit</td>
</tr>
<tr>
<td>PSCAD</td>
<td>Power system computer aided design</td>
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CHAPTER 1
BACKGROUND AND MOTIVATION

1.1 Introduction

Delivering power to customers is a huge challenge that passes through different stages and electric utilities to assure real-time power delivery. The term *real-time* indicates that when a customer uses a switch to turn power on, electricity will be generated, transformed, and delivered at that moment [1]. The conventional electric power system structure shown in Figure 1.1 illustrates the stages of generating and delivering electricity. The system starts at a large generating station wherein electric power is produced using high efficiency generators. Today, fossil fuel generators, solar energy, nuclear energy, wind power, and other sources are used to produce power [1].

![Basic Structure of the Electric System](www.econ.iastate.edu)

As shown in Figure 1.1, once electric energy is produced, it is transformed into high-voltage (HV) power in stations that are located in power plants. This guarantees high efficiency when delivering power to electrical energy consumers. Electrical energy is then transported by HV lines, which are stepped up in power stations over long distances to guarantee highly...
efficient electric power is delivered to consumers. Next, the transmission system carries the HV electricity through HV lines to different locations called substations. Substations are equipped with major types of equipment used throughout the transmission stage of an electric power system. Each type of equipment has a significant function and unique characteristics to assure the efficiency of power delivery throughout transmission. Once in a substation, HV electrical energy is stepped down into low-voltage (LV) power that can be transferred through distribution power lines. The electric power is then delivered to customers through the distribution network.

A primary reason for using HV over long distance power lines is as follows: Increasing voltage decreases current for the same power, which is known as Ohm’s Law. This allows for the use of small conductors, since transport loss is a function of current (squared) flowing through the conductor [1].

To conclude, as mentioned, the final stage in a power system is distribution of the electrical energy, which is delivered to final destinations in the system, including industrial, commercial, and residential consumers. These final destinations are called loads. There are industrials loads served directly, and small loads served from a primary distribution network [2]. Indeed, power systems are much more complex when compared to the basic principles used to divide systems into different portions.

1.2 A Smart Grid Definition

The most recent revolution in electricity network technology is called a smart grid. The term smart grid describes an intelligent, future electric power grid that uses digital technology in monitoring and controlling. According to the U.S. Department of Energy, “A smart grid is an electricity network that can intelligently integrate the actions of all users connected to it,
generators, consumers, and those that do both—in order to efficiently deliver sustainable, economic and secure electricity supplies” [3]. In other words, smart grids integrate information and communication intelligently to improve the electricity delivered to customers [3]. The deployment of smart grids will improve electricity grid infrastructure to better facilitate use of information and control tools. It will also improve the safety, reliability, and financial control services in the grid.

![Image of Electrical Infrastructure and Intelligence Infrastructure]

**Figure 1.2: The Intelligence of New Smart Grid Technology (www.altenergymag.com).**

The most significant goal in the application of the smart grid is to improve safety reliability inside of the grid. Recent studies show that smart grid technology can improve the reliability of electric power systems to increase protection efficiency, and enhance fault detection, isolation, and restoration in the grid. This will reduce the duration of outages and the number of customers impacted by these outages. Furthermore, smart grid technology will decrease power line loss and energy usage to improve system efficiency.

**1.2.1 Why implement the smart power grid?**

A smart grid is a version of the future power grid that employs advanced equipment and services together with intelligent monitoring, control, communication, and smart protection. It is referred to as a revolution in the future of electric power grids because by using applicable
technologies, it is a modern and integrated system. With increased energy demands and the expansion of renewable energy sources, power grid systems must be moderated and improved. The smart grid will integrate all types of electric power sources, and accommodate all means of energy generation and distribution to meet the future demands of energy and its technologies [2].

Quality of power delivery is a major goal of the smart grid that will provide a variety of needs and options at different costs. Furthermore, smart grids will provide advanced monitoring and control by employing intelligent equipment such as digital sensors, electronic switches, smart energy metering, and intelligent and advanced communication systems. Its data acquisition and control systems include interactive software, real time control, and power flow analysis. All different types of renewable energy sources will be interconnected with the energy grid system to improve quality, reliability, and stability by using intelligent and advanced devices.

Figure 1.3: The Regular Infrastructure of an Electricity Grid (www.kennisinbeeld.nl).

Providing advanced technology such as the smart grid requires a smart and intelligent protection system to improve the efficiency of power delivery to customers, and to reduce
outages. Employing the smart grid allows energy consumers to be active participants by providing information and options to control the electric demand balance. The differences between the regular energy grid and the future smart grid system are shown in the schemes presented in Figure 1.3 and Figure 1.4 [1].

![Figure 1.4: After Employing the Smart Grid (www.kennisinbeeld.nl).](image)

### 1.2.2 Smart grid technology layers

A smart grid can be described as containing four essential building blocks called layers, as shown in Figure 1.5. Power is converted, transmitted over long distance, stored from renewable energy sources, and consumed in loads in what is called the physical layer. The following layer is the sensor system, which includes current transformers (CT), voltage transformers (VT), digital relays, phasor measurement units (PMUs), smart meters, temperature, and all IEDs used to provide a reliable, secure, and well-developed system. The communication layer, which plays a major role in collecting information, propagates all retrieved data and information from optimal sensors and intelligent electronic devices (IEDs). The final layer is the decision intelligence layer. It processes information and generates control signals received from sensors that require change in the state of the grid or communication systems [4], [5].
1.2.3 Smart grid requirements and applications

Various requirements must be met to employ smart grids in reality. Interconnected information and communication is essential for new smart grid technology. This includes multidirectional communication technologies. Two-way communication systems improve connectivity between different intelligent devices and components within the power grid system. These devices include high efficient sensors, advanced measurement components, and control technologies. Advanced software and hardware systems are also necessary to provide consumers with information needed to control and balance the power demand. Specifically, when implementing smart technology, advanced security software is required to assure that energy flow and communication operations are efficient and secure within the smart grid system. IEDs are required in smart grid systems to provide advanced digital relaying for protection, fault records, and measurements of any other events occurring in the power grid [7]. In addition, PMUs are needed to increase security and efficiency of protection levels of the smart grid system, besides wide area monitoring, protection, and control (WAMPC).

The major goal of these required advanced devices is to improve the efficiency of power delivery, and to enhance the capabilities of the new technology smart grid [7]. The following
are several technologies that require development and implementation, besides what was mentioned previously:

- Intelligent communication and smart appliances to increase safety and decrease power consumption, and facilitate monitoring and controlling the power system.
- Smart meters that give accurate real-time information display to help consumers respond to the power demand immediately.
- Integrated controlling and monitoring systems of the grid.
- Integrated sensors and controller software.
- High voltage DC (HVDC) transmission.
- Flexible AC transmission systems (FACTS) that are used to integrate renewable energy sources and facilitate long distance transportation of electricity.
- Energy storage to integrate renewable energy sources in the power grid system.

Converting the present power grid system into a smart grid will provide reliable electric power with high quality and efficiency in a clean environment and secure system. This will be achieved through the application of integrated and emerged technologies including energy efficiency, renewable energy integration, demand response, FACTS, WAMPC, HVDC, and every other developed technology for the future grid [7].

As mentioned, smart grid technology integrates information and communication intelligently. The deployment of smart grids would improve electricity grids and facilitate the dissemination of information and use of control tools. This would improve protection and reliability, and reduce the cost of power outages and maintenance [5]. Improved protection would enhance power services to provide accurate and highly efficient electric energy production and transportation. Smart grid technologies and intelligent sources of data and
information such as IEDs could also be utilized to develop and improve fault detection and localization methods. Fault localization and fast self-healing layers would help monitor systems by immediately repairing errors and providing high power quality.

1.3 Problem Description

Current power systems protections utilize a relay, current-based tripping system installed in the power grid. Although some power systems are somewhat modernized with digital relays connected to IEDs within the substation and transmission system, their protection philosophy still relies on regular detection and isolation systems, which spend time and effort during outages. The modification in protection systems that will be used in future smart grids is essential to providing efficient outcomes and improving power delivery to the consumers. The increasing of distribution grid units within the power grid will lead to increased complexity of the protection system. There are, therefore, many questions needing study for this system to be applied:

1. How can future smart protections improve smart grid technology?
2. Which method of protection will be more accurate and efficient for use in the smart grid?

The real answer of these questions is found by replacing regular and old protection systems with improved systems that utilize smart grid technology. Thus, the need to explore upgrading towards smart protection strategies should be studied and addressed.

1.4 Research Goals and Objectives

The objectives of this study were as follows:

1. Determine the reasons for converting present transmission and distribution grid protection structures to intelligent, integrated, and prompt (real-time) responses.
2. Demonstrate how the recent intelligent technology advances the field.
3. Illustrate different improved protection method that can be used to meet smart grid protection requirements.

4. Analyze the best method of fault detection and localization to be stimulated by the smart grid revolution.

5. Deploy existing IEDs and PMUs with optimal sensors to enhance protection systems in smart grids.

6. Apply an advanced self-healing protection system to facilitate the electric power flow within a smart grid.

1.5 Thesis Outline

This thesis is structured in four chapters, including this introduction. These chapters consist of the following:

Chapter 1 provided a definition of power grid systems and described the future of smart grid technology. The stages of power delivery through different power system processes were explained. Smart grid requirements and applications were addressed to provide a general overview of a smart grid definition. Finally, the problem of current grid protection systems was discussed, highlighting the need for their replacement with future smart grid technologies.

Chapter 2 provides an overview of power system protection principles to further illustrate issues in current protection systems, and emphasize the need to create an automated system applied to smart grids. Also, the arguments for developing fast, accurate, and smart protection system schemes for future smart grids are explained.

Chapter 3 introduces a new method and proposes an autonomous outage detection and restoration system using self-healing philosophy.
Finally, Chapter 4 presents the summary of the proposed method, and conclusions and recommendations for further studies and research are given.
CHAPTER 2
OVERVIEW OF PROTECTION PRINCIPLES IN ELECTRIC POWER GRIDS

2.1 An Automated Protection System for Smart Grids

Employing smart grids requires an updated protection system that increases the reliability of the new technology. When a fault occurs in the electric grid, transmission, or distribution system, a wide area of the network is without power, which is only recovered when the fault is cleared. It takes time to find the main cause of the fault and clear it. In fact, one of the most significant and critical factors for power companies is the time spent during fault localization and clearing of the grid [8]. Fast fault clearing reduces the consequence of manpower and economic loss. In this chapter, an updated protection system is proposed. This protection system uses very high-speed protection responses and restoration actions during external or internal faults.

Application of smart grid technology leads to a bi-directional power system and grid that facilitates power delivery and recovery of a fault area rapidly. Continuous power outages are of great concern for power companies and consumers [8]. While faults occur, the voltage drops in the location of the fault. Power companies clear the over-current by isolating the fault area. This results in a sustained electricity outage that takes a period of time to be removed.

Faults in power systems are transient signals that result from a variety of disturbances in transmission and distribution lines. These signals are rapidly fluctuated, and may undergo unexpected variation. Furthermore, transient signals usually cannot be analyzed using a Fourier analysis, the analysis used to transform sine and cosine signals [9]. Transient signals, however, can be modeled and analyzed using wavelet theory, which is used for non-stationary signals.
2.2 Phasor Measurement Units (PMUs)

A phasor measurement unit (PMU) utilizes time synchronization to take real-time measurements of multiple remote points on a grid. These devices are considered one of the most important measuring devices in a smart grid. They can be used as dedicated devices, or they can be incorporated into a protective relay or other device [9].

PMUs are used to detect un-stationary waveform shapes that generated by faults, which is recognized mathematically and called a phasor. A PMU can measure 50/60 Hz AC waveforms of voltages, currents, and phase typically at a sampling rate of 6-60 samples per second [10]. The analog AC waveforms, retrieved from voltage or current signals, are converted from an analog to a digital signal (A/D) for each phase. A phase-lock oscillator, which operates along with a global positioning system (GPS) is used as a reference source, is used to provide the high-speed synchronized sampling with accuracy of 1 microsecond. The consequential time of phasors can be transmitted to a local controller or remote receiver at rates from 6 to 60 samples per second [4], [10].

2.3 Power Grid Sections Influenced When Applying a Smart Grid

Power derived from an electric power grid occurs through three major stages: (1) generation, (2) transmission, and (3) distribution division, the process wherein electricity is delivered to consumers. The most essential parts of power grid systems, which are highly affected by faults, are the transmission and distribution systems. During transmission, electric power is carried using transmission lines to distribute electricity in different loads to consumers. The next section describes transmission and distribution with advanced devices applied within the grid to keep power flow without interruption.
2.3.1 Transmission Systems

Transferring electrical energy from generating stations and units to end of system terminals requires overhead lines and equipment within different stages. This process within the transmission system includes stepping up and down the voltage over sub-transmission and substations [2]. Electric power grid systems have existed for more than 50 years, and this conventional transmission system has remained throughout the passing of time. With increasing power demand, however, the power system grid has been improved in recent years to make it more reliable, and make better use of its advantages.

Beyond increasing power demand, several factors have influenced changes in power grid systems. First, studies conducted over last few years have resulted in increased attention on distributed generation (DG) schemes [9]. Second, the European Union began using alternative energy to substantially reduce greenhouse gas emissions as part of its effort to prevent climate change. According to the Kyoto Protocol, Europe is more advanced in using renewable energy when compared to other places across the globe. Finally, reduction in gaseous emissions (CO2), efforts to produce more efficient use of energy, deregulation or competition, and diversification of energy resources all encourage improvements in the electric power grid of the future [11].

2.3.2 Substations

Substations include the major types of electrical required equipment used in transmission and distribution systems to monitor and control power surge. In substations, the transported HV is stepped down to facilitate the distribution stage by increasing the current while keeping the same power. The main equipment substations consist of includes:

- Transformers
- Regulators
• Lightening disconnect switches
• Electrical busses and feeders
• Reactors
• Circuit breakers and reclosers for protection systems
• Digital and electromechanical relays for monitoring and controlling grid protection
• Sensors
• Static VAR compensators
• Control building
• Preventative maintenance

2.4 Relays in Protection Systems

Relay applications for the protection of power systems have been used for 100 years. Technology employed to construct relays has improved significantly in terms of relay size, weight, cost, and functionality. Relays can be classified based on the applied technology for their construction and use as the following [5]:

• Electromechanical relays: Electromechanical relays were the first type of relays to be widely used in the electric system. Due to the nature of their principle of operation, which is based on a mechanical force to operate the contacts of the relay, they are relatively heavy to operate and not that fast in response when compared to relays constructed with other technologies.
• Solid-state or static relays: These relays are based on analog electronic circuitry that appeared in the early 1960s. Static relays showed significant advantages over electromechanical relays, however; they also presented serious disadvantages.
- **Digital relays**: Advanced digital relays incorporate analog-to-digital-converters (ADC) to sample incoming analog signals, and use microprocessors to define the logic of the relays. High accuracy and integration of multifunctional algorithms constitute fundamental benefits of this technology [5].

- **Numerical relays**: Numerical relays are normally utilized with specified digital signal processor to perform and use particular digital signal processing (DSP) applications.

**2.5 Relay Performance**

Good performance of a relay in a power system is related to the following characteristics [10]:

- **Reliability**: Reliability is the ability of a relay to operate correctly. The two elements of reliability are:
  - Dependability, which is the certainty of a correct operation upon the occurrence of a fault.
  - Security, which is the ability to refrain from unnecessary operation.

- **Selectivity**: Selectivity is the capability of the relay to maintain continuity of supply by disconnecting the minimum section of the network necessary to isolate the fault.

- **Speed**: Speed is ability of a relay to reach a minimum operating time to clear a fault in order to avoid impacts to equipment.

- **Sensitivity**: Sensitivity is the ability of the relay to recognize any changes or abnormal operating situation that exceeds specified threshold value.

**2.6 Improving the Protection System of a Smart Grid**

The future of the electric power grid is expected to improve as new technologies are implemented within the grid. One of the objectives of the future smart grid is to enhance the
protection system to improve efficiency and reliability. In this chapter, the sequences of the self-healing automation in MV and LV grid are discussed by applying several steps to improve the protection system of smart grid. Also, an advanced protection system using a self-healing method in the distribution system of smart grids is introduced with the application of advanced sensors and IEDs. Optimization of electric grid operation includes protection automation is another objective in the implementation of smart grids. Reducing loss and outage time improves the reliability of power delivery to consumers with high efficiency and quality [12].

One aim in deploying self-healing systems in smart grids is improving the continuity of delivering power without interruption. As previously mentioned, distribution is the final stage in the electric power grid, consisting of the delivery of electric power to consumers. Power system automation protection includes fault localization, faulted area isolation, and power restoration to unaffected areas. This is the most essential technique for improving power networks. When faults occur in the distribution systems of power grids, a variation of voltage, current, and phase signals can be detected and recorded using intelligent devices and PMUs, which are distributed in smart grids [12]. These smart devices can be used for locating, and real-time updating and retrieval of data concerning the grid’s status. Nowadays, this includes enhanced scenarios with protection systems using islanding protection, which detects the fault and isolates the affected area promptly from the main grid source. Circuit breakers (CB) are the major cause of outages and power loss, which isolates the main source and feeder to the distribution network site. This makes the islanding protection systems more complicated, requiring the use of low cost advanced electric devices in order to integrate a variety of appropriate protection algorithms, including islanding and reliability [12].
2.7 Power System Communication Network

The operation of electricity grids is monitored and controlled at present by supervisory control and data acquisition (SCADA) systems. SCADA are linked through different communication networks such as microwave and optical fiber networks to assure system operation. They connect transmission substations with the main generators to facilitate an integrated system. The actual operation of communication systems in power grids occurs using lines along the system with advanced optical networks. Loss of these communication wires is possible and could make protection and monitoring the network more complex. Using advanced wireless communication and sensing devices could improve the controlling and monitoring of the whole system.

With smart grid technology and intelligent electronic devices, monitoring and controlling the electric power grid includes HV and LV smart grids. IEDs can be installed and distributed within the grid to be used for advanced electric flow monitoring and protection [6], [12]. These devices are interconnected and can be communicated to the main IED, which is implemented in the substation. Moreover, IEDs can monitor and update the electric flow status in real-time, and can be used to manage and control the grid including the points of HV and LV exchange. Figure 2.1 shows the relations of concepts discussed thus far (i.e., self-healing protection, renewable energy, and advanced devices) to smart grid technology.
Advanced metering infrastructure (AMI) functions, which are deployed by IEDs, are used to retrieve data and information from the grid. The status of this data is then transmitted to a receiver, which is integrated to work with the IEDs. Sensors are installed at each node and branch of the network to update the electric power flow status in real-time. Isolation switches or breakers are integrated and installed at branches and nodes to isolate any affected area when a fault occurs [12]. They are also integrated with AMI to be used in the future with smart grids to facilitate the automation and operation of electric power systems.

2.8 Sensing and Measurements

Faults in transmission and distribution networks can be detected and localized by deploying IEDs within the grid as explained [6]. The over-current element connected in IEDs installed in the grid can detect the fault and operate further processes. The major function of applying smart grids is to deploy advanced technologies and devices to monitor and control the
electric power network [3], [12]. However, applying smart grid technologies in real systems require synchrophasor devices and measurements such as PMUs and IEDs to integrate the electric power grid system [9]. Advanced sensors and real-time monitoring, controlling, and measurement devices enhance the system and improve the efficiency of power delivery with smart grids. They also can be deployed for protection and control for electric power grid [3].

2.9 A New Method of Fault Localization, Isolation, and Restoration of Power

As shown in Figure 2.2, applying advanced communication and intelligent devices will facilitate the power flow in distribution grids. Switch dividers (SDs) are interconnected with the IEDs to be engaged and operated during faults [5]. In Figure 2.2, L1, L2, L3, L4, and L5 are loads connected to the power grid using the same line and feeder for electric flow. A fault occurred between L4 and L5, leading the over-current detector in IED1 to command a main switch to open and isolate the feeder making an outage for all loads connected. The major problem now is how to isolate the affected area and restore the electric power to the rest of loads. New technology besides advanced and intelligent devices can be helpful to avoid the wide range of outage or fault areas. In this scheme, the backup power source could be connected through the regular method in same situation by closing the NOP to provide power from the nearest feeder [5]. However, this method could not work to restore the power to L5 when a different fault occurs on the other feeder [12].
To upgrade the degree of protection used in the same scheme, reclosers in RTUs are connected and linked to IEDs distributed along the feeder and power line, and between loads [6]. As displayed in Figure 2.3, the RTUs with reclosers and switches are installed and distributed along the distribution power line to be integrated with IEDs.

Figure 2.3: Fully Automated Protection System Applied with IEDs and RTUs Along the Distribution System for Future Smart Grids [6].
As shown in Figure 2.3, the IEDs are also installed and linked at the same time to a common communication network. This method leads to the creation of an automated protection system for distribution networks in smart grids [5], [12].
3.1 Introduction to New Methodology Concepts

Distribution is the final stage in the delivery of electric power to consumers. In this stage, electricity is carried from the transmission system after stepping down voltage, and electric power is distributed to different load locations. Applying smart grid technology activates a network of intelligent optimal line sensors and switches to create a self-healing protection system. Self-healing protection systems utilize equipment that restores power automatically when there is trouble, or a fault in the line. This reduces the number of consumers affected by power outages. The components of self-healing systems, such as optimal sensors and IEDs, are connected wirelessly to improve the performance of real-time information updates to the main controller.

Optimal wireless sensors assure that information and signals are sent without interruption by disconnected lines, for example in the instance of a fault occurring. Measurements can be collected in real-time using PMUs or IEDs linked to installed sensors on distribution grids. The infrastructure of a smart grid is very advanced because it uses these intelligent devices for monitoring and controlling.

The first stage in a self-healing protection system is localizing the fault area. The second stage is sending information in real-time to monitor the network. The third stage is controlling the affected area by isolating it from the grid and restoring electricity to the unaffected lines and loads to reduce the outage region. This advanced framework operation reduces cost, time, and the duration of outages, increasing the efficiency of the power grid. In the next section, a proposed framework for the mapping of protection
systems will be illustrated and simulated using power system computer aided design (PSCAD), which applies and tests the new technology using advanced and intelligent equipment and devices to make the power grid smart.

3.2 System Operation

Figure 3.1 illustrates the self-healing protection system method using advanced devices and sensors to deliver electric power with high quality and efficiency. Imagine a traveling wave created by a fault in the grid. Sensors register these traveling waves as transient signals that are different than normal waves in the system.

![Self-healing Protection Network Block Diagram](image)

**Figure 3.1: Self-healing Protection Network Block Diagram.**

The sensors that monitor waves can be installed, as shown in Figure 3.2, along with distribution power lines at fixed distances. Once installed, the sensors can be linked wirelessly to directly engage the head controller in one cluster. Each cluster connects to the main controller wirelessly to facilitate operation of the network, and responds to the fault occurrence rapidly to recover the branches under fault.
3.3 Protection and Fault Localization with Existing IEDs and PMUs

The method proposed in this paper applies all features of IEDs that can be installed and distributed within the grid to control and mange the power system without problems. First, this method could use more technology, which would increase the richness of the information gathered from these intelligent devices. However, as with most advanced technology, the cost of these devices can be inexpensive when compared to the losses in outages and customers. Second, PMUs can be employed in grids, especially in smart grids, and can function to indicate any variation or changes in voltage or current signals. Third, the process of the automated protection could improve the protection system in future grids, considering time as a major factor of the system. Figure 3.3 illustrates the operation sequences when a fault occurs to facilitate the electric power recovery during outages.
Figure 3.3: The Process of Clearing Faults in a Power Grid.

Figure 3.4 illustrates a power system scheme that applies sensors to a typical distribution system. In Figure 3.4, A, B, C, D, and E are nodes wherein IEDs are installed in every node within the distribution and transmission grid. The IEDs used in these nodes are PMUs. This is an equivalent distribution power system to simulate and test a self-healing system with advanced devices installed within the grid.

Figure 3.4: Power System Scheme Applying Sensors to a Typical Distribution System.

When a fault occurs between A and B shown in Figure 3.4, the regular process is:

- Sensors A and B send a signal to the IED, which indicates a variation in current signal, a voltage drop, or other transient signal has occurred.
• Immediately, the IED sends a command to initiate a trip in the substation to isolate the faulted area before the over-current takes a wide area of the grid.

• After installing reclosers in all loads and the affected area, the fault will be isolated in the line. Whenever a fault occurs in the distribution, the fault current must be isolated and interrupted before customers and equipment are affected.

Figure 3.5 illustrates a fault occurring between sensors on point A and B in a grid. The distance between A and B is fixed so that a fault between the two points can be easily located. Point B detects a voltage drop because of the fault. In this situation, the affected area must be isolated and restored rapidly. Therefore, when the fault occurs, the recloser trip sends a signal opening the switch disconnector (SD).

![Figure 3.5: Fault Occurring Between Two Optimal Sensor Points in the Grid.](image)

The recloser and disconnector units are combined in one unit referred to as called the ring main unit (RMU). A possible auto-protection method is as follows (Figures 3.6 and 3.7):

1. A fault occurs in the line between point A and B.
2. Sensor B indicates a voltage drop and sends a signal to the controller station to diagnose the situation and command the closest RMU to operate promptly.
3. Because of a traveling wave caused by the fault, sensor A indicates the voltage drop and sends the update to the head controller.
4. The controller immediately isolates the faulted area by commanding the SD
   connected to sensor A’s closest RMU.

5. The affected area between A and B is isolated using the RMU to trip and operate the
disconnector to prevent an over-current from the rest of the grid.

6. At the same time, it is necessary to restore the rest of the grid affected by the outage
   (C, D, E, and their loads) by using green energy employed in the smart grid.

7. The affected area can then be easily located, as it is isolated between two PMU
   indicators. In this way, fault clearing can be short in time and the affected area is
   limited. Backup sources applied in the smart grid technology and bi-directional
   system also help to restore other affected and nearby areas of the system.

8. Once the fault is cleared, the isolated lines can be restored using the original source,
   which must be synchronized with other sources when disconnected using the RMUs.

Figure 3.6: Before Fault Occurrence.
3.4 Smart Communication Strategies for Smart Automated Protection

Monitoring and controlling the interconnections between distributed sensors along the grid requires a smart, new clustering scheme more suitable to facilitating communication. One scheme is called hierarchical clustering. With this strategy, the protection of the power grid can be controlled and managed using smart and intelligent devices. As shown in Figure 3.8, the sensors in each cluster can be connected to the main cluster head (CH), which transfers information to the controller station. The controller station sends updated data retrieved from the sensors and PMUs, and at the same time manages and controls any changes in the grid. For example, sensors or PMUs in cluster I are distributed within the grid in a specified zone. The CH receives and engages immediately to and from each PMU or IED. Each CH immediately transmits to the controller station to facilitate managing and controlling different aggregations. This strategy facilitates the communication with sensors and PMUs, besides controlling the disconnectors and reclosers in the power lines [8].

Figure 3.7: After Fault Occurrence.
Figure 3.8: Wireless Communication between the Sensors and Controller Station to Monitor the Electric Power Network.

During any fault period, different auto-operations can control intelligent devices so that protection can be employed to the smart grid. In fact, the distribution grid can be divided into different areas for rapid protection using the advanced and smart strategy. Signals between sensors and cluster heads can be sent through wired or wireless connections, which depend on the cost for building this architecture [8]. These sensors can be adjusted to send data when critical changes occur in the power grid. They can also be set to update data and information within a certain timeframe or periodically. Certainly, analyzing and improving power grid protection should be from the far end of load terminals, to manage most outages rapidly.

3.5 Modeling in PSCAD

Our research focused on three stages of operation once a fault occurs within the distribution system in a smart grid. The automation of protection operation systems was used as a control platform and command for an optimized algorithm for a self-healing system to be used in future grids. To learn more about how self-healing protection systems can be deployed in smart grids of the future, a simulation was conducted using to
test once the fault occurs until it is cleared from the grid. PSCAD was selected in our study as the simulation software. A simulation was used with an improved, existing PSCAD model, used for simplifying the distribution grid (DG) system.

3.5.1 First stage

The first stage of the simulation was to locate the fault area procedure using the traveling wave concept, wherein sensors distributed within the grid detect the fault. The deployment of optimal sensors within the grid, especially in distribution site, is the most significant technique for smart grids. PMUs are advanced devices that can measure any variation of the grid status including voltage, current, and phase change. Moreover, detecting traveling waves when faults occur is useful in preventing cascading outages when using PMUs. Sensors can detect any non-stationary signals that are caused by a fault occurrence.

3.5.2 Second stage

After locating the fault, the second stage in the simulation process, self-healing protection, begins. Specifically, when the fault is located using optimal sensors, a signal is wirelessly sent to the main controller installed nearby, as shown in Figure 3.9.

![Figure 3.9: How Sensors Transmit and Receive Signals from the Main Controller.](image-url)
3.5.3 Third stage

The third stage involves isolating the affected area using switches or breakers to avoid fault damages on wide area of the grid. After the controller commands the switches to open and isolate the faulted line, different electric devices called reclosers integrate with IEDs through RTUs to operate promptly after command. Time delay was set to initiate a trip by the relays connected in the substation, which isolated the feeder during normal protection operation, as shown in Figure 3.10. The controller system gathered all updated statuses and data from the RTUs and IEDs in the system to proceed to the next step. The restoration operation after detecting a fault in the grid was:

1. The controller system sends a command to IED, which detects the over-current when the fault occurs. It included switch 1 opening and isolating all areas beyond the point from node A in the scheme.

2. After milliseconds of tripping the faulted area, the controller sends a command to the IED to reclose the switch so that electricity can flow. However, if the fault was still affecting the same area, the sensors updated the over-current signal wirelessly to the main controller system, commanding the switch to open again and isolate the area.

3. Meanwhile, the main controller system, which connected with all sensors and IEDs at this area, sent a command to isolate the exact affected area, where the fault occurred between two sensors on points A and B.

4. A command was then sent to the alternative source, applied by smart grid technology, to operate and restore electricity back beyond the outage area, as shown in Figure 3.10. Finally the affected fault area is isolated and electric power is restored to other areas that could be affected.
3.6 Results of the Automated Protection Experiment

Results show that using advanced and intelligent devices deployed within a smart grid could save time and effort when restoring and reducing outages areas. As shown in Figure 3.11, the current signal flowed until the fault occurred, phase A to ground fault, within 0.3 sec. After that, the initial trip went a few seconds later to the feeder, which isolated all connected areas before and beyond the affected line. The fault caused a trip to open the main switch from substation side, which led to an outage in the rest of the area. At second 0.35 sec., the recloser connected to the IEDs at the same line affected by the fault to restore the electric power, test and gather further information and status line data in real time, and check if the fault was cleared as a short-term fault. This operation took 0.025 sec., until the controller commanded the switch before the faulted line to open again and proceed to the next operation to isolate and restore the rest of the connected lines and loads. The operation was sent wirelessly, and took only milliseconds to assure the outage’s time was reduced for unaffected areas, and restored promptly.
Figure 3.11: The Result of a Self-healing Protection System Displaying the Sample Voltage Signal.

As shown in Figure 3.11, the electric power was restored to the area beyond using an alternative power source, applying smart grid technology using renewable power to have a complete micro-grid system.

Figure 3.12 shows a picture of the operation sequences using the self-healing and automated protection system that was simulated using a typical distribution power system with the same power source, loads, and fault condition.

Figure 3.12: The General View of Self-healing Process Sequences Using a Proposed Method for Smart Protection Applied and Simulated by PSCAD Software.
As shown in Figure 3.13, each phase signal was displayed to obtain the impacted phase that resulted from the enforced fault, which in this simulation was phase A to ground fault. In this situation, the reclosers were not used to restore the electric power immediately after fault occurrence, and the fault took a period of seconds to be restored to other unaffected areas and loads.

Figure 3.13: Decomposition of Voltage Signals Retrieved from a Three-Phase Power System Showing the Sequences of Fault Localization, Isolation, and Restoration to the Rest of the Power Network Loads.
CHAPTER 4

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

4.1 Summary and Conclusions

In this thesis, a framework to facilitate a protection system’s monitoring and controlling of power grids using advanced technologies applied in smart grids was explored. The framework’s methodology included fault detection and localization, faulted area isolation, and electric restoration to the unaffected areas of the grid. Our proposed framework and methodology consisted of the following:

1. Fault detection and localization using advanced technology and devices including IEDs, PMUs, and optimal sensors installed along nodes and branches within the distribution grid of the power system.

2. A method of sending all updates between sensors and the controller will be established and thus creating a cluster of wirelessly networked of sensors. The controller based on exchanged data will allow for proper action to take place when a line is disconnected.

3. The controller system will be designed to monitor the cluster and control the fault clearing procedure automatically. By using such a system, the protection was self-healing to reduce the duration of outages.

4. If a fault occurs, the system will respond naturally to isolate the line by tripping the relay from the main bus to open the switch.

5. Immediately, the controller commands in factions of seconds to reclose the underlying main switch. If the fault is persistent, then the controller command will be to open only the switches associated with the two sensors after recognizing the
location of the fault and reclose the main switch by which it restores the power to the rest of cluster.

6. In the case of a fault still affecting the recognized line, our proposed methodology was utilized to monitor and automate the distribution power grid using IEDs and sensors. The method isolated the affected area using RTUs, and included switches to disconnect the faulted line from the grid. Then, the majority of loads beyond this area were restored using the advanced technique of the smart grid that deployed renewable energy from nearest load areas to generate electricity back into the grid system. The areas before the isolated faulted line were restored using the normal electric power source.

The enhanced self-healing methodology and framework of this work was simulated using PSCAD to test the ability of a protection system to be managed and controlled with highly advanced techniques. The results of the simulation were obtained by applying the methodology on a retrieved three-phase electric voltage signal. A hierarchical clustering scheme was most suitable to deploy the technique of wireless sensor networks in the smart grid. The mapping framework enhanced the protection system to improve the distribution grid’s monitoring and controlling by applying all tasks automatically once the fault occurred. The equivalent system was applied in PSCAD software to test the same situation and parameters of a real distribution power grid.

The proposed framework can be applied to the distribution grid system, which has many branches, lines, and nodes, making it difficult to detect or clear faults rapidly. Reducing the duration of outages and the wide impact of faults is an essential goal of improving protection systems for smart grid technology. Self-healing protection should
improve the process of protecting smart grids with advanced technologies, and increase the reliability of electric power delivered to consumers, while also narrowing down blackout areas. Localization using sensors with electric restoration in a short time to unaffected networks will reduce the costs of power outages. This automated protection mechanism can also provide intelligent sequences of organized processes when the fault occurs. These stages can be controlled automatically and can be handled to facilitate the power grid system.

4.2 Recommendations

Self-healing protection systems can be improved by increasing the number of sensors and main controllers to allow for better coverage over the power grid with a cloud of communications that operates wirelessly within the smart grid various devices and elements. In future research, extensions of this proposed framework for the self-healing protection systems should investigate algorithms to localize the exact fault spot on the grid line with classification of type of fault. A wavelet transform based algorithm that has the same features of transient signals generated by the fault can be a very appropriate path to investigate. These un-stationary signals can be detected and used to feed into the localization algorithm which in turn will compute the distance between the fault location and the associated sensors. With this method, the self-healing protection system can be combined to improve the fault localization, making it more accurate and efficient.

Finally, future research should examine deploying more IEDs and PMUs to monitor and control the distribution grid using a main controller programmed to respond rapidly and process needed sequences to avoid power grid trouble. Regarding other
improvements, the islanding system technique and its improvement using different types of power sources feeding the same power grid area could be explored in the overall improvement of smart grid and smart protection to have even more efficient outcomes and power delivery.

4.3 Conclusion

Smart grid technology integrates information and communication intelligently into electric power grids. The deployment of the smart grid will improve electricity grids, especially information and control tools. This will improve protection and reliability, and reduce the costs of power outages and maintenance. Smart grid technologies and intelligent sources of data and information could be utilized to develop fault detection and localization methods. Detection and localization will be improved by employing smart grid technology and IEDs. Improved protection will enhance power services by providing accurate and highly efficient electric energy production and transportation. Indeed, self-healing protection systems that include fault localization, isolation, and restoration will help monitor the system by immediately making repairs, and responding to improve power efficiency and quality. The new technique of self-healing power system is a smart way to prevent disturbance’s damages.
BIBLIOGRAPHY


