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Pro-active Selfhealing – An Extensionconcept in SmartGrid

Noman Nisar
Electrical and Automation Department
Aalto University
Espoo, Finland
noman.nisar@sharif.edu.pk

Jay Panchal
Electrical and Automation Department
Aalto University
Espoo, Finland
jay.panchal@aalto.fi

Abstract— *The reliability of power system under fault susceptible environment has become major challenge for the power sector units. The injection of renewable power source has increased the complexity for distribution system and to deal with massive network, evolution of smart-grid has been enforced, which works in an automated fashion to improve overall reliability, efficiency and quality of the system. Proactive Self-healing is a critical feature of smart-grid. This paper tries to explain the concept sensing the occurrence of fault beforehand and providing possible solution for self-healing in smart grid. The fundamental base for incorporating afore discussed technology viz. understanding nature of fault, sources of fault and implementation of effective measuring techniques are enumerated in paper briefly. Support required in terms of technology is reviewed towards the end followed by a case study of practical implementation of self-healing control in a distribution system.*

Keywords—Pro-active self healing, smart grid;

I. Introduction

The pro-active diagnostics schemes for the online condition monitoring and assessment of the network components is one of the major requirements for the emerging smart grid technology. The increase in demand for system reliability and power quality calls for improvement in existing network condition assessment methods. Self-Healing property of smart grids is the key solution to the increasing complexity in the network. Conventionally, the concept of self-healing in the power distribution network was limited to identification, isolation and rapid restoration of the faulted system or network component in order to minimize the interruption and keeping the system reliable. However, the modern concept of self-healing network also requires an efficient methodology for early detection of fault development and rectification of the cause before fault occurrence. The latter concept is known as pro-active self-healing. All these concepts require thorough understanding of electrical faults nature that a distribution network may face. A brief overview of faults type and their nature is provided in next section.

II. Understanding the Nature of Faults in the Distribution Networks

The nature of fault depends upon the location and type of the equipment in the distribution network. A partial discharge is one of the abnormal conditions which need to be detected at early development stages before they change into permanent faults. Besides that, there are types of faults which occur immediately due to equipment malfunctions, unintentional human or animal interaction with the energized system and these are hard to detect. Underground Cable Network, Transformers, and MV Switchgears etc. are more prone to fault. The factor leading to these faults are over voltage, faulty connections, ambient stresses, defects in insulation. In addition to these overhead conductors face small fault current due to falling trees.

III. Pro-Active Self-Healing

As discussed in the former section, the primary need for the self-healing network is early detection and diagnostics of the incipient/arc faults in the distribution network. Different methods can be categorized into pro-active or reactive depending on actions taken to detect the developing faults.
Figure 2.1 represents the different actions and methods that can be used in the fault detection and prevention [5]. The arc ignition is predicted by different sensor technology but besides use of sensors, periodic maintenance of equipment can also lower their probability of occurrence. Visual inspection, partial discharge tests, thermal imagining are few examples of periodic maintenance.

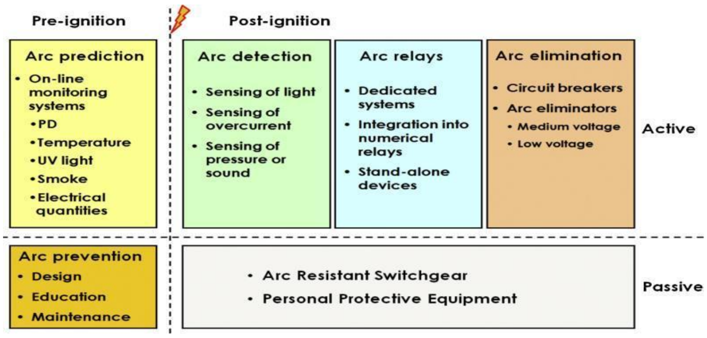

Figure 2.1 Categorization and comprehensive view of arc-fault protection [5]

A. Electrical Fault Prediction

The preemptive fault detection techniques require the deployment of online sensors for continuous monitoring of the arc-flash development phenomena.

B. Detection by Analysis of Phase Currents:

Arc prediction is possible by performing a complete harmonic analysis for the high frequencies and frequencies in between the harmonics of the normal load current. The third harmonics is considered as an indicator for low power arc faults but these are not reliable in non-linear load conditions.

C. Analysis of current differential:

This method is used for detecting the arc faults across the cable terminations. A similar scheme to current differential protection can be used in this case. Figure 2.2 shows the cable termination monitoring which compares the current before and after the termination [5].

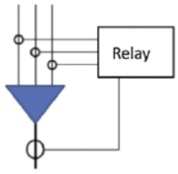

Figure 2.2 Monitoring of Cable Termination

Physical Quantities indicating Developing Faults are Electromagnetic Emissions, Acoustics (Ultrasonic) Emissions, Optical Emissions, Thermal and Chemical Emissions. Detection of these signals with different dedicated sensors can help to identify the location of fault.

The most commonly used sensor technologies are:

a) Induction Sensors: HFCT and Rogowski coils are the type of induction sensors which can detect and measure high frequency current pulses.

b) Thermal Sensors: Special type of sensors knows as IR sensors are used for online monitoring and arc prediction in system.

c) D-Dot Sensor: The D-Dot sensors measure the change in the flux density D. The sensor is made from the SMA jack. They can be directly installed to the surface wall or insulation material under observation.

d) RF Antenna: The electromagnetic energy emitted by the discharge processes can be detected with the antenna which converts electromagnetic signals into electrical signals. Widely used types of RF antenna are biconical, loop, log-periodic etc.

IV. Integration of Self-Healing Network in Smart Grids

The implementation of self-healing network in the smart grid technology requires an efficient and automatic restoration methodology for power outages. Compare to traditional distribution network the intelligent devices and evolution of smart meters in smart grids has increased the observability of the power systems network [6].

A. Smart grids against traditional distribution networks

A brief comparison of the traditional distribution network with smart grids is presented below [6].

1) Generation: Unlike traditional power network, smart grids variety of distributed generation systems are scattered across the whole distribution network which increases the reserve capacity and makes network flexible and effective for self-healing.

2) Power Consumption: With the evolution of smart meters, it is now possible for the DNOs (Distribution Network Operators) to receive real time energy consumption data and allows bidirectional communication with consumer. This increased power reliability of network.

3) Network Topology: Smart grid provides network topology with many possible alternate paths and meshed network scheme, which was the limitation with traditional network.

4) Observability and Controllability: The use of IEDs (Intelligent Electronic Devices) in smart grids allows monitoring, control and automation of the network. The traditional distribution network uses SCADA system which has problems regarding the real time measurements.

5) Restoration Method: The rapid restoration of the power by the use of IEDs and artificial techniques are the key benefits of smart grids. The faults are cleared conventionally by operating the manual switches and sending the troubleshooter to the faulted site which results in larger time interruptions and costs.

B. Self-Healing System Structure

Self-healing network can be divided into two groups [5]:

1. Component Layer
2. System Layer

The component layer is subdivided further into primary and secondary components. Primary components include the network main equipment's for example transformers, circuit breakers, etc. The secondary components include the protection and automation devices. The application of self-healing network in the component layer is either to be pro-active fault diagnostics or it can be reactive for quick repair or substitution of the equipment as discussed in further section. The system layer works on the principle of minimizing the effect of outage by isolating the fault and reconfigure network to achieve normal state. Traditionally, the system layer self-healing in distribution systems is conducted via distribution automation (DA).

1) Distribution Automation (DA)

Distribution automation in smart grids is the backbone in achieving the high reliability, power quality and for the integration of distributed energy resources [3]. DA is a set of technologies that enable an electric utility to remotely monitor, coordinate, and operate distribution components in a real-time mode from remote locations [3]. The implementation of DA has many benefits which can be classified according to the specific application. One of the most popular applications of DA is Fault Location, Isolation and Service Restoration (FLISR)

2) Fault Location, Identification and Service Restoration (FLISR)

FLISR is used in smart grids as a DA application for performing the self-restoration scheme. Implementing FLISR allows the automated isolation of the faulted section with the help of advanced switching and protective devices and apply restoration algorithm to minimize the interrupted customers (figure 4.1). By using FLISR, the power restoration to the healthy sections takes place quickly by using the fault location algorithm and schemes, avoiding the time lapse in patrolling and waiting for the faulted system isolation by manual switching.

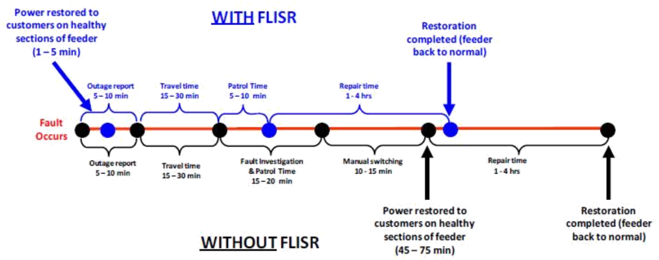

Figure 4.1 Comparison of reliability improvement due to implementation of FLISR versus conventional restoration [6]

Fault location in distribution systems reduces the outage time and eventually the outage cost. Improving the key performance indexes CAIDI (customer average interruption index) and SAIDI (system average interruption duration index) by quick fault detection methods results in reliable and efficient power system. The fault location techniques are categorized according to the type of the observed data used to obtain the fault location [4]. There additionally are many methods to counter this, which is discussed below:

a) Apparent impedance measurement: The method uses the ratio of voltage to current measured at the fault indicators placed along the feeder. But problem with this method is fault location depends on measurement of particular date and method is not cost effective.

b) Superimposed components: This method utilizes the superimposed voltage and current values. In this method, an assumed fault point is varied systematically until the actual fault point is found [4]. However, this method also has a major drawback of giving multiple fault location estimations.

c) Power quality monitoring data: The occurrence of fault causes voltage sags across the network. The voltage sag has different characteristics depending on the location of the nodes. This characteristic can be used for detecting the exact fault location.

d) Artificial intelligence: Using the protective device settings for training an Adaptive Neuro-Fuzzy Inference System (ANFIS) can be used for detecting the faulted area. But it requires large training data due to complexity and changing network.

3) Automated Fault Location Technique using smart grid IEDs:

The IEDs are now used as an essential part of smart grids, located all over the network for the monitoring, protection and distribution system automation.

The power quality meters with the capability to record transients are installed at the different points along the feeder. The proposed methodology matches the voltage sag waveform patterns measured at different points. For analysis, Power flow algorithm is used by application of fault at each node and results are compared with voltage sag data. The highest similarity observed is considered as the exact location of the fault. The voltage mismatch can be given by the following equation [6]:

$$\delta_k^{i,j} = V_{k,med}^{i} - V_{k,sim}^{i,j}$$

Where,

$V_{k,med}^{i}$ = Magnitude of the during fault voltage sag at node i

$V_{k,sim}^{i,j}$ = Magnitude of the during fault voltage sag at node i by applying fault at node j

Similarly fault location index is used to ensure the correct spotted node by the following equation:

$$\eta_j = \frac{1.0}{\max[\max(\delta_k^{i,j}) - \min(\delta_k^{i,j})] + \Delta}$$

Where,

$i = 1, \ldots\ldots, mp$

$j = 1, \ldots, mn$

k phase a, b or c

mp: Number of voltage measurement nodes

mn: mp number of voltage measurement nodes

Δ: Small number in order to avoid zero in denominator

For algorithm to work on the exact fault location, the measured voltage and current phasor required to be time synchronized and this can be achieved by phasor measurement units (PMU).

Fault Detection and Isolation

In the modern smart grid network with the involvement of distributed generation, the fault point can be powered from several directions. This requires complex tripping methodology which may results in multiple breakers tripping. The present network topology and state of the circuit breakers are required in order to determine which breaker should be tripped to isolate the fault [2].

A new fault detection and isolation algorithm of distributed network with distributed generation is proposed in [2]. To describe the network topology, matrix L (node branches incidence matrix), and fault information matrix G is used. The fault section matrix P is obtained by multiplying both G and L as,

$$P = G.L$$

Further two matrices Q and D are used to define the states of switches and breakers in the network according to the relation

$$D = P.Q$$

Where Q defines the relation between the each line and switch and P is the same fault section matrix and D will give the final solution for the switches to be turned off in order to isolate the faulty section.

For analysis of fault detection algorithm, consider the following network shown in the figure 4.2 having multiple distributed generation sources line sections.

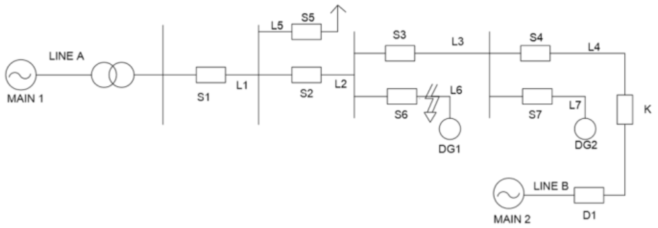

Figure 4.2 Network Model for Fault Detection and Isolation

The above mentioned matrices can be created according to the network topology with the fault at line section 6. The elements of matrix L are defined as:

$$L_{ij} = \begin{cases} 1 & node\ i\ and\ branch\ j\ are\ connected \\ & and\ j\ is\ in\ the\ positive\ of\ i. \\ -1 & node\ i\ and\ branch\ j\ are\ connected \\ & and\ j\ in\ opposite\ of\ i. \\ 0 & node\ i\ and\ branch\ j\ are\ not\ connected \end{cases}$$

The element of matrix G has value 1 if the fault current is in the positive direction, -1 if the direction is negative and zero otherwise.

The same algorithm can be implemented in different case by correcting the elements of the fault information vector G when the tie breaker is open. Depending upon the definition of positive direction, we need to modify the matrix G in order to make the calculations easier to discriminate between positive and non-positive faults. Mathematical operators are required to modify the matrix G in following way:

$$g_i' = \overline{g_i \oplus 1}\ \ for\ the\ branches\ and\ g_i' = g_i \oplus (-1)$$

Where $\oplus$ represents Exclusive OR (XOR) operator

In the figure 4.2, S1-S7 including D1 represents the section switches whereas K is the tie switch. L1-L7 are the branches for the network model. Using the above description, the elements of matrix L can be obtained below as,

$$L = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Now for the fault at section 6, S1, S2, S6 detects the positive direction of fault current while S3, S7 detects the negative direction of fault current while S4 and S5 doesn't detect any. So we can have the corrected fault information matrix G as $G = [1\ 1\ 0\ 0\ 0\ 1\ 0]$. Now using the equation $P = G.L$, the fault section matrix comes out to be, $P = [0\ 0\ 0\ 0\ 0\ 1\ 0]$. Since Matrix P directly represents the faulty element if its value is 1 hence there is indeed fault at L6. This algorithm can then be used in order to detect the fault location.

Since the fault section matrix P gives only the section where the fault is, it is usually essential to find out the switches as well as breakers which can play a key role in isolating the fault. For the fault isolation, the element of matrix Q is defined as:

$$Q_{ij} = \begin{cases} 1\ node\ i\ and\ branch\ j\ are\ connected \\ 0\ node\ i\ and\ branch\ j\ are\ not\ connected \end{cases}$$

Now, as shown in the figure 4.2 the fault is at section 6, the measuring points m=7 as S1 to S7 and the tie switch K is closed only in case of faults for backup supply. The fault section matrix P for the fault at section 6 is [0 0 0 0 0 1 0]. The breaker information matrix is

$$Q = \begin{bmatrix} 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The breakers which needs to be tripped are given by matrix $D = P.Q$ which results in [0 0 0 0 0 1 0]. The switch S6 must be tripped to isolate the fault completely.

The tie switch, whose presence improves reliability of network, remains open under the normal operating conditions. But as an example, in case of fault at location L2 of the network under study, the switches S2, S3 and S6 needs to be switched off to isolate the fault completely. In this case the tie switch will close to provide the supply to remaining healthy sections. The algorithm can be modified for coping with changing network topology by defining the matrix K representing the breakers state of the network. The elements are defined as:

$$K_i = \begin{cases} 1 & switch\ is\ closed \\ -1 & switch\ is\ open \\ 0 & unknown\ switch\ state \end{cases}$$

Where, $i = 1, 2, \ldots, n$ and n is equal to the number of switches in the network.

Now for the changed network, with fault at section 3 i.e. L3, supply from the main source, breaker S3 open and tie switch K closed, the matrix G [0 0 0 -1 0 0 -1] and modified matrix G' is [1 1 1 0 0 0 0]. Fault section matrix P is now given by [0 0 1 0 0 0 0] indicating the fault is in section 3. The modified trip

switch vector *D'* is [0 0 1 1 0 0 1]. Therefore it requires S3, S4 and S7 to turn off to isolate the fault completely.
This algorithm works efficiently in fault isolation for the complex networks with distributed generation sources and also performs even after the change in network topology.

Service Restoration

Quick and efficient service restoration after the occurrence of fault results in saving the outage costs and improved performance key indices SAIDI, CAIDI and SAIFI of distribution network. That can be achieved by shifting the effected load to different branches through the appropriate switching operations. Implementation of micro grids and islanding of DG can provide reliability solution for the different networks.
Reconfiguration of distribution loads are usually done by switching operations of network sectionalizing switches and reclosers. The service restoration algorithms works on the principle of achieving the optimum operation scheme of the minimum number of network switches for maximum load recovery without overloading the supply network.
One such algorithm based on the tree-structured grid is given in [1]. The flow chart of algorithm is given in the figure 4.3. Before explaining the working of algorithm, few operational rules and targets must be considered [1].
According to the flowchart, the first thing to do after the fault location is to discover the outage area and loss power quantity. After marking all the switches in the outage area, count the number of switches which can be operated between the supply area and outage location given by ‘n’. If there are no such switches to operate then self-restoration is not possible. However, if n≠0, select a root node in the outage area. All other nodes are structured in the tree. Switch the root node and

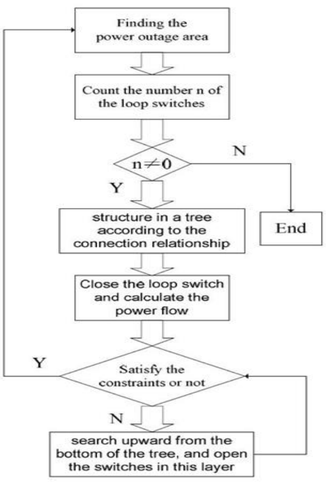

Figure 4.3 Flow Chart Algorithms for Service Restoration

check the power flow constraints. If match is found, that means the self-restoration is successful. If not, keep switching next upward node in the tree until satisfying the constraints. This simple algorithm can be extended to provide solution for self-healing reconfiguration of the distribution network involving the independent operation of Distributed generator.

V. CASE STUDY

In this paper, a MATLAB setup is developed to elaborate the concept of self-healing which can be visualized as an extension concept in smart grids in the later phase. A MATLAB model presented here represents that of a real network having three phase programmable voltage source, circuit breaker as well as three phase series RLC load. To explain the concept of self-healing, a fault is generated on the load section with the help of timer and the corresponding values are measured with the help of VI-measurement unit.
Figure 5.1 shows the Simulink model used in the case study. A subsystem block, shown in figure 5.2, is also designed within this to generate reclosing operation which gives its output signal to the circuit breaker to ensure self-healing operation. Whenever this subsystem senses faulty condition, it locks out after three operating cycles as is the setting for the reclosing action, if the fault is not cleared before that. If for instance, a fault is cleared before the locking, it will try to restore the supply in order to have self-healing of the network.
Different types of faults like Single line to ground fault (SLG), line to line fault (L-L) or double line to ground fault can simply be implemented with fault block in the Simpower Toolbox and the corresponding impact on the network can be seen.

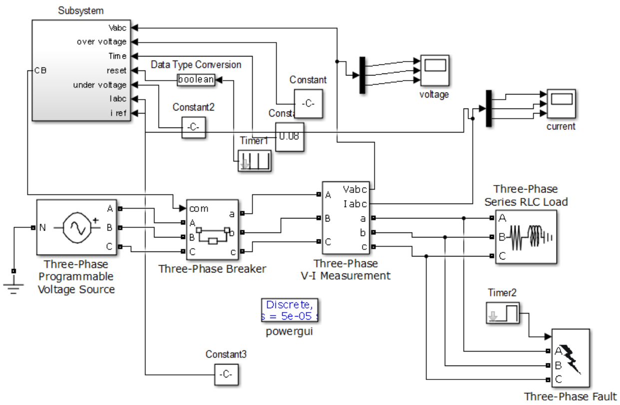

Figure 5.1 Power system case study Simulink model

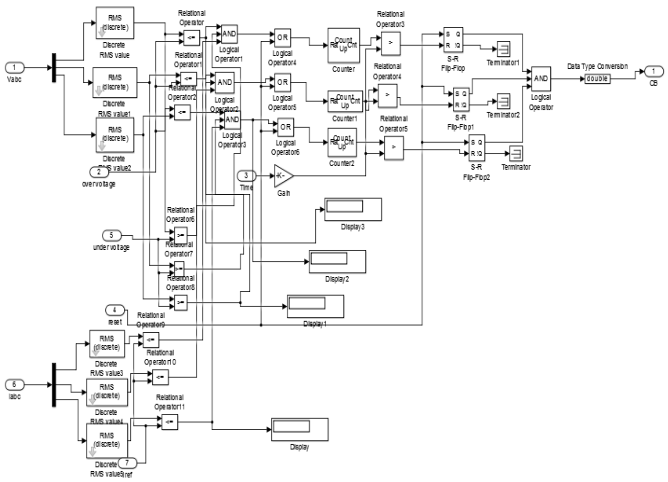

Figure 5.2 Subsystem model in MATLAB Simulink

Since the network models in MATLAB can be simulated both in discrete as well as in continuous modes, the power system model presented here is modeled in continuous mode as the continuous model is more accurate.

VI. RESULTS AND DISCUSSIONS

In order to test the operation as well as the performance of the model developed, a three phase fault was simulated and the results are presented here:

The first phase of the case study deals with the fault generation and gives the settings of the parameters in such a way so that the network trips if the fault hasn't cleared before three operating cycles. The state of the timer for energizing of the network is [0 0.1 0.33] with an amplitude of [0 1 0] which means a system is energized at 0.1s and completely de-energized after 0.33s. The initial state of the circuit breaker is also kept open.

Time and Amplitude settings for the generation of fault are:

Amplitude (p.u) [1 4 1 4 1]

Time [0 0.15 0.19 0.26 0.32]

So a fault of two cycles is from 0.15s to 0.19s and from the figure 6.1 it can be seen in output waveform that circuit breaker didn't trip, but for fault of three cycles from 0.26s to 0.32s circuit breaker gets a trip signal from relay and it opened.

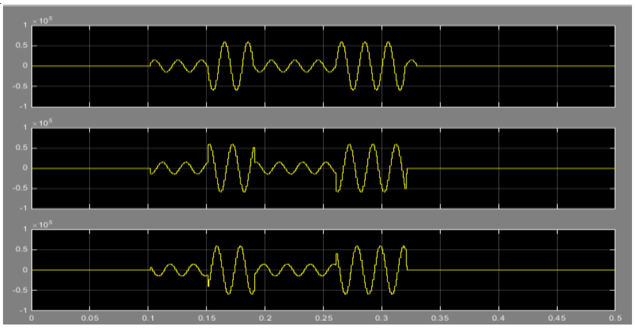

Figure 6.1 Circuit breaker operation followed by a fault

The next phase of the case study deals with the self-healing action of the power system network following a faulty condition. The parameters of the implemented Simulink model have been modified in such a way as to not only trip the network supply in the faulty phase after three operating cycles of fault has passed but also to restore the supply after the fault has been cleared with the help of timer (implemented in Simulink). Figure 6.2 and 6.3 shows the scenario of after fault occurrences and during the recloser operations.

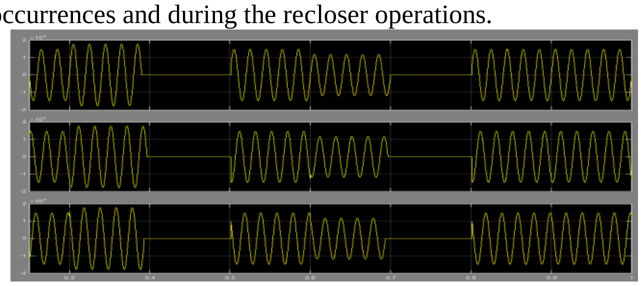

Figure 6.2 Current waveforms in three phases showing the self-healing action.

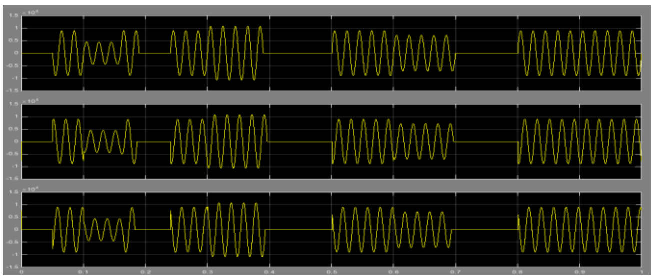

Figure 6.3 Voltage waveforms in three phases showing the self-healing action.

VII. CONCLUSIONS AND FUTURE WORK

This paper reviews the self-healing property in the smart distribution grid. The distribution network has undergone a vast development in recent past with the accelerated interest growing in smart grids all over the world. The smart grids brings numerous advantages by providing a better possibility of monitoring and observing the system condition. The key feature of smart grid is self-healing. Self-healing techniques discussed suggests that by careful consideration best use of the network assets can be achieved. Deployment of smart equipment in the network allows for an automated system which can cope with the catastrophic situations quickly. Besides that the improvement in system reliability greatly reduces the key performance index factors CAIDI, SAIDI and SAIFI which gives financial benefits to the distribution companies.

In future, the network will be integrated with more distributed generation resources, energy storage banks, micro grids and electric vehicles which will make the existing network more complex. Accordingly, the technology and algorithms must also develop.

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