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# *Procedure of Fault Management in Distribution Networks with DG*

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To obtain the degree of Electrical Engineer

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*I would like to extend my sincere thanks to my advisor Professor Mario Alberto Rios for his guidance throughout this project.*

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# Content

# Chapter 1

# Introduction

Continuity and quality are two indispensable terms to ensure the satisfactory operation of an Electric Power System (EPS). Continuity of the service acquires special importance when you have in mind that electricity cannot be significantly stored and that any interruption will have a direct and immediate impact on almost all processes in the industry. In the same way, quality becomes an indispensable requirement to guarantee the correct operation of the equipment connected to the network.

When a fault occurs in the EPS, magnitudes associated to this reach values outside of their normal operation ranges and some areas of the system can start to work unbalanced, losing continuity and quality of the service. Therefore, the design of an electric system must contemplate the occurrence of aleatory and unexpected faults, and design a protection system that would minimize the effects of these faults in the system.

The classical challenges of electrical protections are being lately altered by a trend to power systems more energy-efficient, reliable, and environmentally friendly. This trend is giving a start to concepts as DG and is bringing new technical challenges for engineers in several fields. One of these fields in which the impact of this trend is important, is in electrical protections [8], as the functionality and reliability of the system depends on it. The main effect is given by the constant change in the topology of distribution systems, which alters the conditions that were initially used for the adjustment of the protection devices. For this reason, modern protection systems should be able to adapt themselves to the continuous changes, keeping the basic criteria of sensitivity, selectivity, and speed, demanded by a coordinated and reliable system. Besides, since electrical distribution systems are increasingly bigger and interconnected, it is important not only to focus on the immediate reaction upon faults, but also to have in mind that must exist a complete fault procedure, from the detection of fault to the efficient and fast restoration of the energy supply in the entire power system.

Connecting generators to a distribution network would change its properties significantly. Mainly, the short-circuit currents will vary and its flow paths will be more complicated. On the other hand, a fault clearing will cause a big change in system's topology and will allow some part of the network, if is possible, to operate in island mode. Therefore, some problems that appear are loss of selectivity, earth-leakage protection, disconnection of generators, and islanding among others [9]. As a consequence, classical protection techniques may become inadequate and protection parameters will have to be updated frequently.

Several researches have been performed on how to tackle the resultant problems of applying DG into distribution networks and on how to maximize the benefit of such changes for increasing reliability on the system. For example, in [12][5][23] adaptive protection schemes have been stated and some of them have been implemented on part of a real distribution network, showing the advantages of using such schemes. Other, like [18][15], have tried to show the microgrids operation, protection and control issues, and its possible solutions. In [23][13][11], the proposed schemes are based on a zoning procedure and its main objective is to adjust and maintain coordination of some protective devices placed between the determined zones. Almost all of them are thought with micro-processed relays with a communication module. Additionally, this subject has caught the attention of different control areas, e.g., [7][25][26] have proposed schemes that are based on a multi-agent architecture, where each digital relay in the system is an agent with the ability to process information, take decisions, and interact with other agents. Although the proposed solutions have been different, all of them agree that shutting down all DG when a fault occurs can be impractical and that is necessary to implement an adaptive philosophy in the protection schemes.

Given the importance of protection systems to ensure the continuity and quality of the electricity supply service, the objective of this project is to state a procedure of fault management in radial systems when DG is incorporated. In order to meet this objective, it is necessary to establish the required steps to detect faults, isolate faulty zones, detect and create possible island modes, and finally restore the total operation of the system. Besides, the proposed procedure should identify the required adjustments for the protection devices involved in the system. Furthermore, a computational tool is developed to show the proposed procedure in an interactive simulation environment, which gives information about the system and its protection devices as well as messages in each step of the protection procedure after a change in the system is detected. As mentioned earlier, throwing off all DG from the system every time a fault occurs would make the system very unreliable. Thus, the whole protection procedure is based on an independent adaptive scheme that would not undermine the system reliability after connecting DG.

# Chapter 2

# Electrical Protections

Modern design of power systems provides different strategies to decrease probability of faults, however is economically and physically improbable to remove them totally. Thus, an appropriate reaction to the occurrence of faults becomes completely necessary in order to mitigate its effects on the system. Fault management is undoubtedly one of the most important functions to decrease the outage times in the electricity supply. This management includes everything from fault detection to both partial and total restoration of the energy supply in the system.

A fault or perturbation is defined as any unplanned change in the operation variables of a power system. These faults can be caused by different internal or external reasons and present undesired consequences on the operation of the system and its integrity.

**Causes:**

- Atmospheric discharges. (External)
- Breaking of conductors, insulators and structures due to earthquakes, winds, snow, vandalism, among others. (External)
- Insulator damage caused by animals or environmental factors. (External)
- System operation switching. (Internal)
- Energization of equipment. (Internal)

**Consequences:**

- Equipment overheating, lines incineration, increase of line sag.
- Severe voltage fluctuations.

- Unbalance that cause inappropriate operation of equipment.
- Instability of power system.
- Outages in the electricity supply.
- Severe damage to equipment or people.

There is a general classification for faults in electric power systems, which identify them according to its duration:

**Transient or Temporary Faults:** This kind of faults are due to momentary situations that cause anomalies in the system and can be cleared before serious damages occurs either because they are self-cleared or because the fast action of a protection system. The clearest examples of these faults are atmospheric discharges or momentary contacts of lines with the branches of trees.

**Permanent Faults:** This kind of failure persists despite the intervention of protective equipment and cannot be cleared until the direct intervention of maintenance personal. Some of the clearest examples of these faults are the break of lines, falling of support structures and the equipment breakdown in the system.

## 2.1 Fault Analysis

There are several tasks in the power system, electrical protections mainly, that require a precise knowledge of the values associated with faults occurring in the system. Such values are obtained through fault analysis, in which the fault current levels, short circuit capacity and pos-fault voltages are calculated.

The formulation of the analysis of faults in sinusoidal steady state, is understood if is analyzed the behavior of the main source of the short circuit current in the power system, the synchronous generator. The figure 2.1 shows the short circuit current of a synchronous generator.

From figure 2.1 is clear that current in the generator begins with a high value and tends to decrease over time, so that three periods can be distinguished. The first one associated with the biggest current value, known as transient current (I”), the second one known as subtransient current (I’), and the last one known as steady-state current (I). The direct-axis reactance of the generator corresponding to each period or current value is denoted as Xd”,

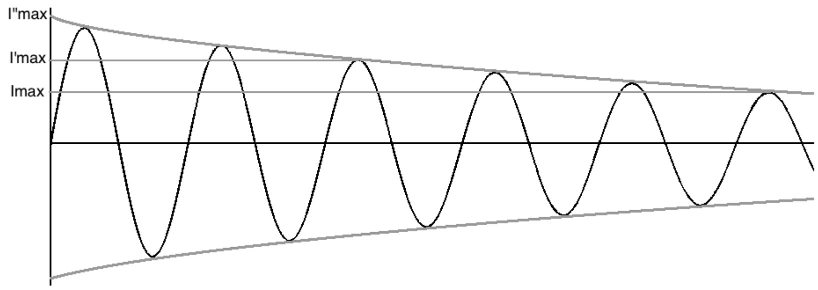



Figure 2.1: Short circuit current in a synchronous generator [21].

Xd', and Xd respectively. The behavior of these two variables in a synchronous generator after a fault occurs are shown in 2.2.

The phenomenon associated with the occurrence of a fault, has certainly a dynamic character. However, due to the variables of interest and knowing the required amount of fault analysis, this phenomenon is analyzed in steady-state. For the purpose of this dissertation, short circuit analysis for three-phase fault and mono-phase fault are going to be considered.

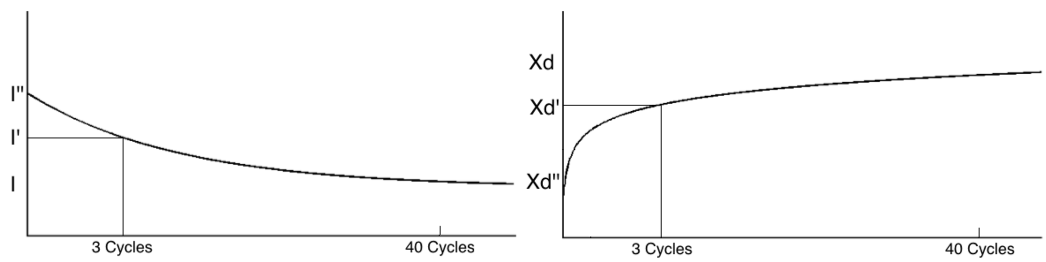



Figure 2.2: Behavior of current (Left) and reactance (Right) after a fault occurs [21].

### 2.1.1 Three-Phase Faults

This faults are considered as symmetrical faults, keeping the balance of the system (three equal currents out of phase in 120 degrees). The fault can occur between the three lines or between the three lines and ground. By keeping the system balanced the calculations are easier as shown below [1].

$$I_{3\phi fault} = \frac{V_f}{Z_{TH} + Z_{fault}} \tag{2.1}$$

where $I_{3\phi fault}$ is the fault current, $V_f$ is the voltage just before the fault occurred, $Z_{TH}$ is the Thevenin impedance in the fault site, and $Z_{fault}$ is the fault impedance. Is important to note that normally the system is in a common base (p.u) and if so, the voltage just before the fault occurred is taken as 1 p.u.

A common way for this calculation in computational means is the use of the impedance matrix ($Z_{Bus}$, which has inherently the Thevenin impedance of each bus in its diagonal. So, assuming that the impedance matrix is in p.u, the equation would be given by 2.2.

$$I_{i3\phi fault} = \frac{1}{Z_{ii} + Z_{fault_{p.u}}} \tag{2.2}$$

where $I_{i3\phi fault}$ is the fault current in the bus $i$, $Z_{ii}$ is the value of the element $ii$ in the impedance matrix, and $Z_{fault_{p.u}}$ is the fault impedance in p.u.

### 2.1.2 Single-Phase Faults

These are called asymmetrical faults because the balance of the system is lost. In this case is required an analysis method that provides a convenient way to deal with the asymmetry problem. This is why in 1918, Charles Legeyt Fortescue, demonstrated that any set of N unbalanced phasors could be expressed as the sum of N symmetrical sets of balanced phasors, for values of N that are prime. Only a single frequency component is represented by the phasors. Essentially, this method converts three unbalanced phases into three independent sources, which makes asymmetric fault analysis more tractable [21].

So, three unbalanced vectors of a three-phase system can be decomposed in three balanced systems of vectors. These three balanced systems are designated as:

- Positive sequence components, which consist of three phasors of equal magnitude, separated $120^o$, rotating in the same direction as the phasors of power system under consideration.

- Negative sequence components, which consist of three phasors of equal magnitude, separated $120^o$, rotating in the opposite direction as the positive sequence.

- Zero sequence components, which consist of three phasors equal in magnitude and in phase with the others, rotating in the same direction as the positive sequence phasors.

Thus, the relation between voltages and currents of any three-phase system and its symmetrical components is defined by the matrix relation 2.3.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} \tag{2.3}$$

where $[V_a, V_b, V_c]$ are the phase voltages, $a$ is the operator defined by $1\angle 120^o$, and $[V_{a0}, V_{a1}, V_{a2}]$ are the zero-sequence voltage, positive-sequence voltage, and negative-sequence voltage, respectively. The matrix relation works in the same way for currents.

In the same way, in order to analyze an asymmetrical system all the impedances must be expressed as positive-, negative- and zero-sequence components. The line impedance is equal for positive and negative sequences but different for the zero sequence. For generators and transformers, positive and negative sequences are modified just in the impedance value, but the zero sequence impedance in these cases is a little more difficult to find. The figure 2.3 shows zero sequence connections for generators and the figure 2.4 shows zero sequence connections for transformers.

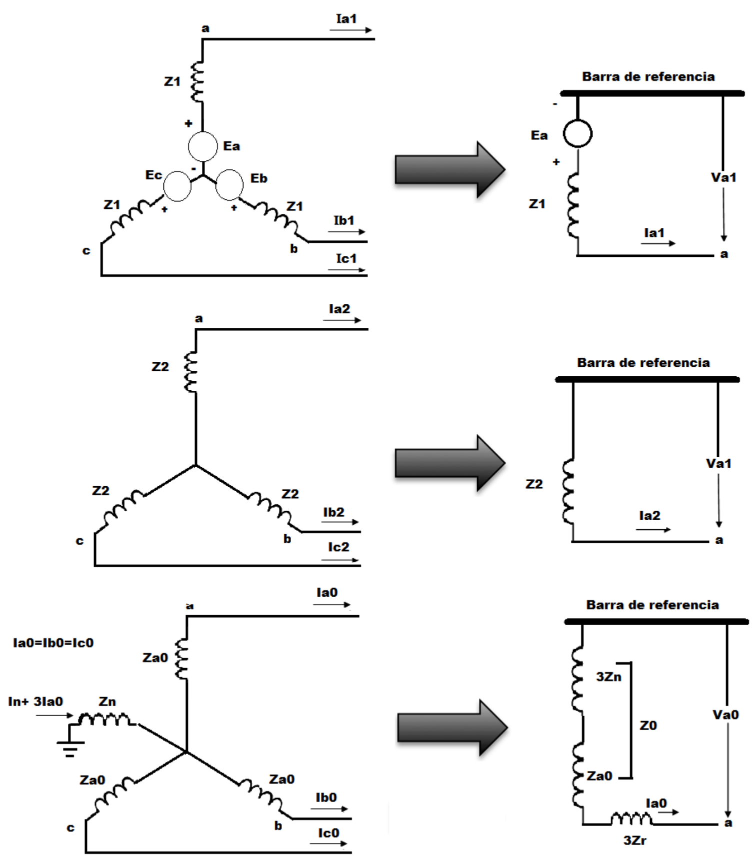



Figure 2.3: Equivalent zero sequence networks for generators [21].

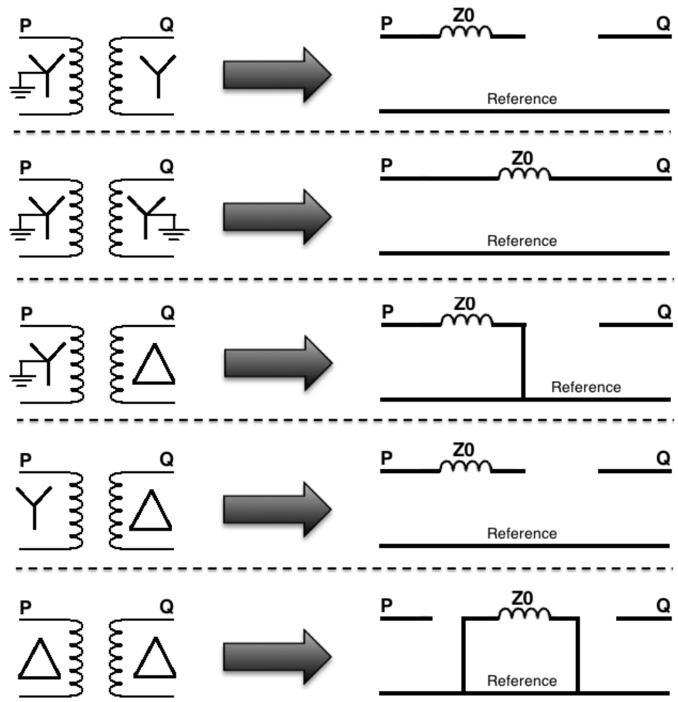



Figure 2.4: Equivalent zero sequence networks for transformers [22].

Now, in order to calculate fault levels using the method of symmetrical components is essential to determine the individual impedances of sequence and combine them to build the correct sequence circuits. Then, for each type of failure, the appropriate combination of sequence circuit is performed to obtain the relationship between voltages and fault currents. Given this and using the impedance matrix method, mono-phase fault current can be defined as shown in equation 2.4.

$$I_{i1\phi fault} = \frac{1}{Z_{1ii} + Z_{2ii} + Z_{0ii} + Z_{fault_{p.u}}} \tag{2.4}$$

where $I_{i1\phi fault}$ is the fault current in the bus $i$, $Z_{1ii}$ is the value of the element $ii$ in the positive-sequence impedance matrix, $Z_{2ii}$ is the value of the element $ii$ in the negative-sequence impedance matrix, $Z_{0ii}$ is the value of the element $ii$ in the zero-sequence impedance matrix, and $Z_{fault_{p.u}}$ is the fault impedance in p.u [1].

## 2.2 Protections of Radial Systems

Electrical protections are set of equipment and elements that meet the objective of detecting abnormal operation conditions in the power system in order to safeguard the integrity of equipment and people, and to maintain normal conditions so that an acceptable service can be provided. It is important to clarify that a protection system will not prevent faults, but in case of the occurrence of a fault it reacts to lessen or eliminate the effects on the system, isolating the detected fault as soon as possible and trying to maintain continuity of the service in most of the system. As a secondary function of protection systems would be the indication of fault location and fault type [6].

The basic cycle comprising a protection system begins with the measurement of various parameters which are altered each time a fault occurs, such as voltage, current, frequency, angle's phase, power factor and polarity. These parameters are taken up by transformers due to the magnitudes handled and then are sent to a relay which decides if exists an abnormal condition and sends a signal to a switching device in order to take action and minimize the effects of this failure on the system. The basic process of a protection system when a fault occurs is shown in 2.5.

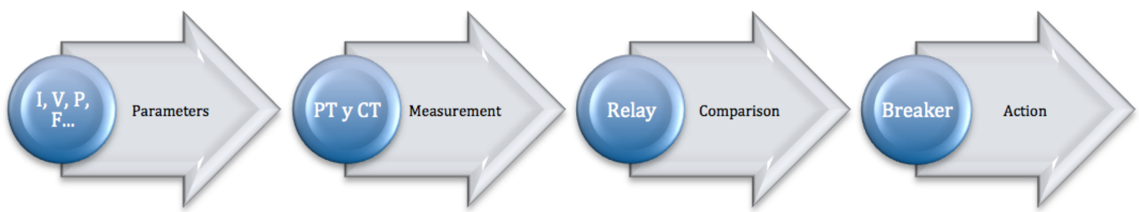



Figure 2.5: Basic process in a ESP when a fault occurs.

Among the functions to be performed by a protection system are: isolate permanent faults, minimize the number of faults, minimize the effects of temporary faults, prevent equipments damage, minimize troubleshooting time, minimize partial or total restoration time of the system, among others. These functions must be met to ensure the following features in the ESP [10]:

- **Selectivity:** Allows to discriminate the location of the equipment or element affected.
- **Speed:** Operation in the shortest possible time after a fault.
- **Sensitivity:** The protection system must operate for all faults no matter how small.
- **Security:** Protections should ensure operation in all cases required.
- **Support:** Secondary protection must operate if the primary did not.
- **Coordination:** Selecting and setting protective devices to clear a fault and/or isolate the affected part.

The general philosophy of a protection system is to divide the electrical system in defined zones that are adequately protected and that can be disconnected when a fault occurs within any of them, allowing the system to continue in service as far as possible [4].

That is why the protection of electrical systems is considered a demanding task that requires different engineering principles either to develop fault current calculations and determine the nominal features of equipments as to coordinate properly each of these in the system. There are several devices to meet all the requirements presented above, however for the purpose of this dissertation we will focus only in overcurrent protection devices for distribution networks.

### 2.2.1 Overcurrent Relays Coordination

Coordination of overcurrent relays is necessary to obtain selective tripping. The first rule of protective relaying is that the relay should trip for a fault in its zone. The second rule is that the relay should not trip for a fault outside its zone, except to back up a failed relay. This coordination will ensure that the backup relay has sufficient time delay to allow the primary relay to clear the fault [28]. In general overcurrent relays to a characteristic function, which gives the operation time of the relay in terms of its load current, its pick-up current and a time multiplier setting.

$$t = \frac{\alpha * TMS}{((I_{Fault}/I_{Pick-up})^{\beta} - 1} \tag{2.5}$$

where TMS is the time multiplier setting of the relay, $I_{Fault}$ is the maximum fault current through the branch and $I_{Pick-up}$ is the pick-up current of the relay, which is given by the load current multiplied by a factor, typically 1.5 for distribution circuits. The constants $\alpha$ and $\beta$ determine the type of curve of the relay's operation, its values are shown in table 2.1.

### 2.2.2 Reclosers

A recloser is a circuit breaker equipped with a mechanism that can automatically close the breaker after it has been opened due to a fault. Unlike conventional circuit breakers and fuses, which require a technician to visit the site of an open breaker or blown fuse to restore service caused by to the fault, a recloser can automatically attempt to close the circuit. Since most overhead power line faults are transient (i.e. caused by a lightning strike), the use of reclosers is very important in distribution networks.

Since the beginning of reclosers, its philosophy has been framed by an automatic reaction; however, due to the new challenges presented by power systems, reclosers are evolving to

Table 2.1: Form constants for exponential equation by IEC

| Type of Curve | $\alpha$ | $\beta$ |
|---|---|---|
| Standard Inverse | 0.14 | 0.02 |
| Very Inverse | 13.5 | 1 |
| Extremely Inverse | 80 | 2 |
| Large Inverse | 120 | 1 |

more complex systems integrating microprocessors, communication modules, remote controls, among several other new features. This has led to the development of systems known as smart reclosers.

There are several companies developing new technologies for reclosers, among which are Siemens with its Type SDR Distribution Recloser [19], ABB with its three-phase recloser OVR [2] and Noja Power with the OSM recloser [16]. These and other companies are trying to improve recloser features to be used in smart grids protection and control. A block diagram that shows the some of the modules and features that can have "smart reclosers" is in figure 2.6.

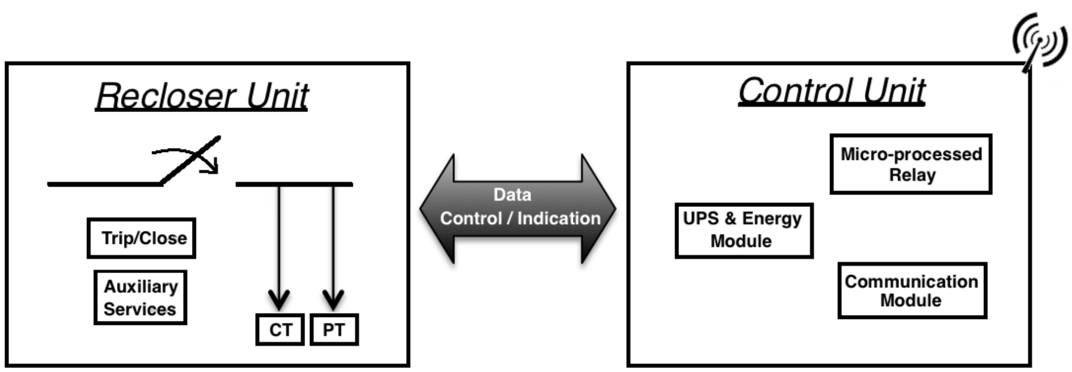



Figure 2.6: Smart recloser block diagram. [16]

## 2.3 Distributed Generation

Current literature does not use a consistent definition of DG, which varies specially in terms of type of resource and capacity. For the purpose of this project we will take a general the definition given in [3], where DG is defined as electric power generation within distribution networks or on the customer side of the meter.

The continuous grow of electricity demand, and the need of modern society for a secure and high quality supply, has led DG to be one of the most relevant topics not just for the electric field but also for all engineering areas, due to the numerous challenges that this entails. The table 2.2 shows the general advantages and disadvantages (Challenges) that brings the incorporation of DGs on the current power system [9].

Table 2.2: Advantages and Disadvantages of Distributed Generation

| **Advantages** | **Disadvantages (Challenges)** |
|---|---|
| Reduction of losses in transmission and distribution networks. | Requirement of new schemes for the operation and maintenance of such systems. |
| Increase in reliability and service quality if regulations are met. | Higher investment costs, especially for some renewable technologies. |
| Greater control of reactive power and voltage regulation. | Greater decentralization can hinder the system's security guarantee and even increase the operating costs. |
| Better adaptation to changes in demand. | Environmental hearing pollution near consumers, in some cases. |
| Increased competition and market power would decrease. | |
| Greater flexibility, reducing dependence on centralized system. | |
| Efficient use of energy sources and incorporation of cleaner resources. | |

One of the main issues that should be analyzed in networks with DG, is the impact of it in electrical protections. The setting of electrical protections is based on the current state of the system, so it is evident that any change would alter system parameters and would make inadequate the classical protection techniques. Moreover, current distribution systems are planned as passive networks, carrying the power unidirectionally from a generator downstream to the loads, so it is also clear that incorporating distributed generators would change the initial philosophy of the system. The main issues regarding electrical protections when DG is incorporated, are shown below.

- It would affect the short-circuit amplitude, direction and duration.
- It would reduce fault detection sensitivity and speed.
- It would reduce reach of impedance relays.
- It would affect the voltage profile and cause reverse power flow.
- It could cause improper islanding and auto-reclosure.

One of the simplest protection issues when connecting a distributed generator is illustrated in figure 2.7.

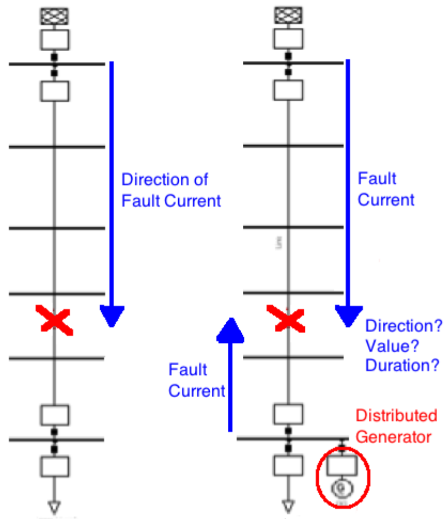



Figure 2.7: System without DG (Left) and with DG (Right).

## 2.4 State of the Art

In the last years, some adaptive protection schemes have been proposed to ensure the correct adjustment of protection functions based on the requirements of the power system. Some of these works are shown in 2.3. Several of this schemes are based on communications networks, which would have to meet all the requirements of some standards as IEC-61850 or IEEE-1547.

Table 2.3: State of the art, adaptive protection schemes

| **References** | **Description** |
|---|---|
| [12], [11], [23], [13] | The proposed schemes in this references are based on a zoning procedure. The main objective of these schemes is to adjust and maintain coordination of some protective devices placed between the mentioned zones. Almost all of them are thought with micro-processed relays with a communication module. |
| [7], [26], [25] | These proposed schemes are based on a multi-agent architecture, where each digital relay in the system is an agent with the ability to process information, take decisions, and interact with other agents. These are decentralized schemes with a zoning procedure proposal in the system. |
| [20], [27], [24] | These schemes are based mostly in communication networks. The protection devices are programmed in a remote mode. The reconfiguration process is based on offline calculations and a very extensive events table. |

# Chapter 3

# Adaptive Management of Electrical Protections

Many researchers in their first approach to this topic said that if protection scheme is not changed, the only way to maintain coordination of protection devices in presence of an arbitrary amount of distributed generators is to disconnect all DG instantaneously in case of fault. However, this solution is not practical as it wastes the advantages of DG on helping with reliability on the system, so is important to think in protection systems with an adaptive philosophy. More specifically, we have to consider the incorporation of protections devices that modify its adjust parameters automatically, based on the operating conditions.

Traditional protection schemes of radial systems are based mostly on fuses and relays located in distribution substations, these devices react when a fault occurs and isolate the part of the system where the anomaly is located. Later, when the faulted element is fixed, human intervention is needed in order to restore the electricity supply to the corresponding circuit. If a distributed generator is introduced, some adjustments should be made manually to the protections devices and besides, as mentioned earlier, a fault in any bus of the system would mean the disconnection of all distributed generators in the system until the fault is fixed. This behavior is not suitable for the future conditions of power systems and even is not optimum for the current necessities. Hence, the following items must be taken in mind in order to meet the requirements of an adaptive philosophy in the electrical protection system.

- For the purpose of having an appropriate response to anomalies in the system, the protection devices should be able of making an automatic reconfiguration, this means without human intervention.

- Protection devices must have a communication module, which would help in the correct operation and coordination of the devices to have the best possible operation.

- If a fault occurs, distributed generators should be able to attend part of the demand in order to increase the reliability of the entire system. This action of isolating part of the system to operate in an independent way, should be made without human intervention.

In view of these considerations, a procedure for managing faults in systems with DG is going to be given. This procedure would be based on an initial operating condition of the system, which would be given by certain zones in the system determined mainly by the capacity and location of distributed generators.

## 3.1 Zoning Procedure

An ideal system would have a recloser device in each one of its branches, however this is economically infeasible, thus a pertinent zoning of the system is needed. These zones would be determined by the location and capacity of each distributed generator. The idea is to start at nodes with DG and extends each zone downstream as long as the DG within it is capable of supplying the peak load of that zone. When the peak load of the zone exceeds DG capacity, the end of the zone is reached, and a recloser must be placed in the beginning and in the end points of the zone, if such points are connected to other zones. If another DG is found while the zone extends, the zone keeps growing until generation capacity of both is reached. It‘s important to note that, when DG's capacity is higher than the load located in its downstream network, zone extension should be considered upward. The size of the zones that do not have DG should not be too large, so if a new DG is placed it can attend the demand of the zone. Clearly, the final decision of the amount of reclosers and thus the size of the zones will be always influenced by economical factors.

With this procedure the system will be divided into two categories of zones. First, zones without DG, so their load is fully supplied through the main source. Second, zones which includes at least one DG and are able to operate in island mode. The final scheme of the system, after the zoning procedure has been carried out, is shown in figure 3.1, where each zone represents a group of nodes of the system.

## 3.2 Proposed Protection System

So far, its clear that the aim of this protection procedure is to appropriately coordinate and control the recloser units that divide each zone, taking advantage of DG to improve the reliability of the system. To meet this objective, is essential to determine the equipment features that are needed and state an operation philosophy for the protection system.

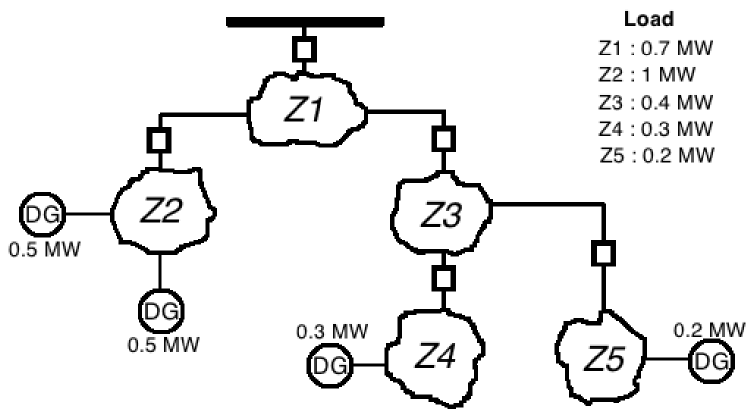



Figure 3.1: Radial distribution system divided into zones according to their DG capacity.

The procedure that is going to be stated is centered only on the recloser units between zones; however, other devices will be appointed in the procedure to ensure the correct operation of the system. As mentioned earlier, the reclosers between zones will have to respond appropriately to any fault and adapt themselves to any change in the topology of the system, so each recloser must be able to communicate with others and reconfigure its adjust parameters. For this purpose, automatic reclosers with a bunch of new features are needed [19][2][16]. Besides, the idea of the system is to increase reliability, thus the wisest decision would be to propose a decentralized architecture, which would require all the mentioned features. As a first approach, a very simple architecture that meets the purpose of the protection system stated is shown in 3.2.

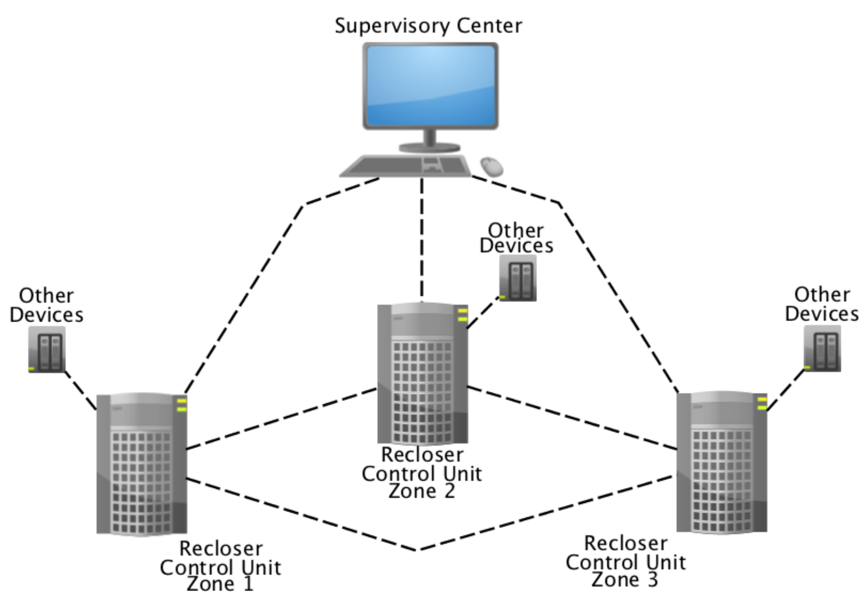



Figure 3.2: Proposed decentralized architecture with a supervisory center.

In this architecture, all the recloser units interact with each other and with other devices in an independent way, so the supervisory center, as its name implies, will just ensure that the system is operating correctly, gather some information of the system and send some information signals to the reclosers. Below, are going to be described the interactions between devices and is going to be stated the procedure of fault management.

## 3.3 Procedure of Fault Management

The expected behavior of the system can be briefly described in three stages, as shown in figure 3.3. These three stages represent the adaptive philosophy that, as mentioned earlier, is required to increase the reliability of radial systems with DG.

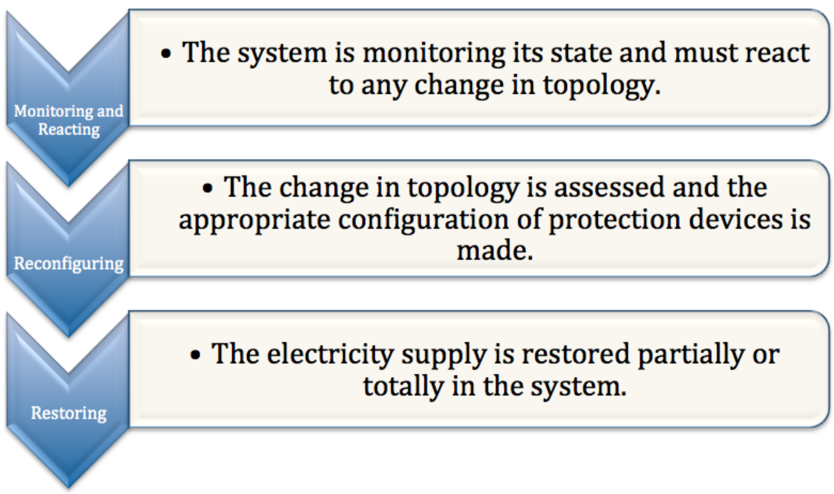



Figure 3.3: General procedure of the system when a fault occurs.

Initially, when the system is operating in normal conditions, the recloser units are monitoring to detect a fault or a change in DG. If a change in DG is detected, the system has to process the change and reconfigure appropriately the protection devices. On the other hand, if a fault is detected, the corresponding recloseres have to automatically clear the fault and all the DG located in that zone, is disconnected. After this, the possibility of each zone to operate in island mode is assessed and the islands are created. The system would have to adjust again appropriately the protection parameters. At this moment, the system will be divided into three types of zones: zones without electricity supply, zones operating in islanding mode and zones supplied by the main source. The system keeps working in this way until the faulted element is fixed, after this the system has to be restored. This restoration process has to be properly carried out, with a correct synchronization between zones, in order to ensure a correct operation in the system.

The flowchart developed for a detailed description of the proposed procedure is divided in three stages, which represent a general cycle of the system. The description of each stage is presented below as well as the associated flowchart in the figure 3.4.

- **Normal Stage:** The system is operating in its initial conditions. The end of this stage is given by a fault occurrence and the reaction of the protective devices.
- **Island Stage:** The system creates islands and operates with islanding modes. The end of this stage is given by the correction of the fault.
- **Restoration Stage:** The system is brought back to the normal stage just after the whole system is synchronized and protective devices are reconfigured.

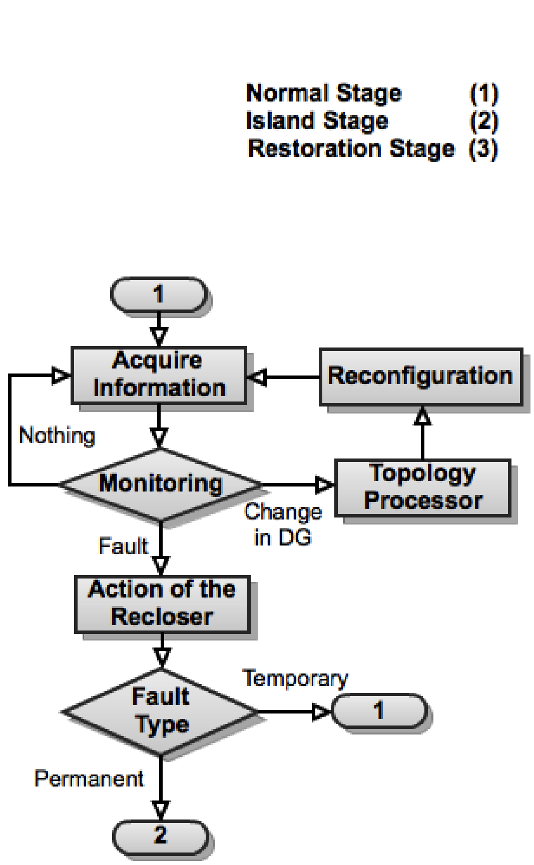



Figure 3.4: Flowchart of the system process after a fault (Procedure of fault management).

In a more specific way, the procedure of fault management would be represented by the next steps. The agents involved in each task are specified.

| **Procedure of Fault Management in Distribution Circuits with DG** | |
|---|---|
| 1: | Acquire information from measurement devices. (Equipment: PTs and CTs) |
| 2: | Monitoring the system. (Equipment: Relays and humans) |
| 3: | If a distributed generator gets in, make changes in virtual topology for calculations and reconfigure protection parameters. (Equipment: Software and Reclosers). If a fault is detected, the recloser acts to decide which type of fault have occurred. If it is a temporary fault, keep the breaker closed. If it is a permanent fault, keep the breaker opened. The recloser that detected the fault, sends all the necessary signals to the rest of the system. (Equipment: Reclosers) |
| 4: | Possibility of islands is assessed and if it is possible, the island is created. (Equipment: Software, reclosers and other control devices) |
| 5: | Make changes in virtual topology for calculations and reconfigure protection parameters. (Equipment: Software and Relays) |
| 6: | Acquire information from measurement devices and monitoring, until the fault is fixed. (Equipment: PTs, CTs and humans) |
| 7: | Synchronize the zones operating as islands with the whole system and close zone breakers. If the recloser does not have a synchronization function, DG has to be disconnected and then connected again when the recloser is closed. (Equipment: Reclosers) |
| 8: | Repeat step 5 and then go again to step 1. |

Below, an specific description of each block of the flowchart is presented as well as its implementation in the algorithm proposed for the application of the procedure in a distribution system.

## 3.4 Simulation Tool

The implemented algorithm is intended to show the proposed procedure of fault management in a simulated radial system environment with DG. The algorithm was implemented in the software MatLab [14] using the package Matpower [17] for solving power flows. The algorithm is based on the flowchart showed in figure 3.4. Next, each one of the blocks in the flowchart is described.

### Acquire Information

The process of acquiring information consists in the measurement of the system parameters and in receiving signals with relevant information. In this task, the measurement module of the recloser unit gets the parameters needed to detect a fault, and the communication module waits for any signal from the other devices of the system.

In the algorithm implemented, this task is simulated as a standby while the user choose an action to do from a menu displayed. The menu is composed by six possible options; get information of the system, cause a fault, fix the fault, include new DG, eliminate DG and exit. The interface of the tool developed is shown in annex A.

### Monitoring

The monitoring process takes the acquired information and process it in order to discriminate the type of change occurred in the system. In this context, the relay module of the recloser is responsible of detecting whether a fault has occurred, and the communication module receives information and detects the type of change in DG. The action of the system is given by the results of the monitoring process.

In the algorithm implemented, there is a submenu to get the information needed in each option. This will simulate the monitoring process and discriminate the change in the system. The information requested by each option is showed below.

- Cause a fault: In this case, the algorithm asks the number of the branch and whether the fault is temporary or permanent. If the branch is already faulted, a message will be displayed asking for a new number of the branch.

- Fix a fault: The algorithm will ask the number of the branch. If the branch is not faulted, a message will be displayed asking for a new number of the branch.

- Include new DG: In this case, there are two ways of including DG; entering all the values of the generator manually or choosing a predetermined generator. There are in the algorithm two predetermined generators.

- Eliminate a DG: The algorithm will ask the number of the bus where the generator is located. If there is not any generator in this bus, a message will be displayed asking for an other bus.

Having in mind that, in proportion, is more common a temporary fault in distribution systems, the usage of reclosers is essential. In the reclosure process, the recloser is tripped one to four times to detect if the fault was already cleared, if not, the recloser will remain open.

### Topology Processor

The topology processor is responsible for incorporating all the changes detected in the system, in order to actualize the state of the system after a change has occurred. Then, some computations have to be made in order to adjust the protection devices to the new operating condition.

In the algorithm, after a fault occurs, all the required changes are made in the system matrices and two main computations are made, as shown in figure 3.5. This will give the information needed to coordinate the reclosers after a fault has occurred.

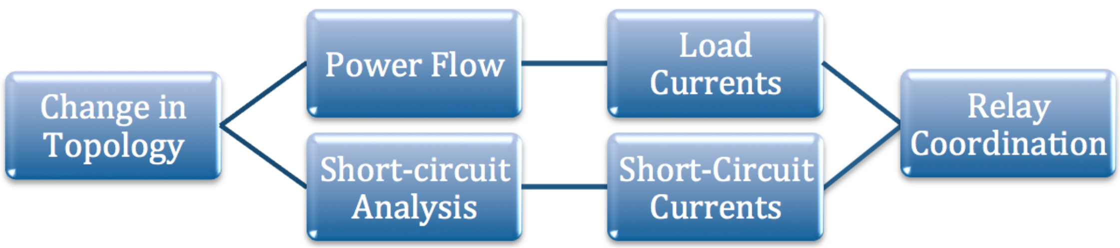



Figure 3.5: Computation made in the Topology Processor block.

### Protective Devices Reconfiguration

Some changes in the topology of the system, depending on their size, would cause discoordination between protection devices. That is why, these equipment must be reconfigured after such changes are detected. The reconfiguration process must be automatic, in order to preserve the philosophy of the proposed procedure.

The proposed methodology for the reconfiguration process, states the coordination of overcurrent relays as a linear programming problem. A solution of this problem would try to minimize the sum of the total operation time of the relays. This operation time is given by 3.1, where $I_{fallaj}$ is the fault current by the relay $j$, $xI_{ni}$ is the pick-up current of the relay $i$ multiplied by the ratio of the current transformer, and $TMS_i$ is the time multiplier setting of the relay $i$. $t_{ij}$ is the operation time of the relay $i$ for a fault in $j$.

$$t_{ij} = K_{ij} \times TMS_i \qquad , \qquad K_{ij} = \frac{0.14}{(I_{fallaj}/xI_{ni})^{0.02} - 1} \tag{3.1}$$

These operating times must comply with the back-up margin given in the equation 3.2, which in distribution circuits is commonly taken as 0.3 seconds. Additionally, it is important to have in mind the limit values of the $TMS$, taking the lower restriction as the dominant 3.3.

$$t_{back-up} - t_{main} \geq 0.3 \qquad \longrightarrow \qquad -t_{back-up} + t_{main} \leq -0.3 \tag{3.2}$$

$$-TMS_i \leq -TMS_{iMinimum} \tag{3.3}$$

Now, it is clear that the objective function of the optimization problem would be given by the sum of the own operating times of each relay, with constraints given by equations 3.1, 3.2 and 3.3. Finally, the whole problem can be written as shown in equation 3.4.

$$\begin{aligned} \underset{X}{\text{minimize}} \quad & [f][X] \\ \text{subject to:} \quad & [A][X] \leq [b] \\ & [A_{eq}][X] = [b_{eq}] \end{aligned} \tag{3.4}$$

Where:

X: Column vector with unknowns of the problem.

$$X = [t_{ii}, \ldots, t_{nn}, t_{ij}, \ldots t_{nn-1}, TMS_i, \ldots, TMS_n]^T$$

f: Row vector with the coefficients of the objective function. The first n positions are 1, the rest are 0.

A: Matrix of terms located at the left side of the inequality constraints.

b: Column vector of terms located at the right side of the inequality constraints.

$A_{eq}$: Matrix of terms located at the left side of the equality constraints.

$b_{eq}$: Column vector of terms located at the right side of the equality constraints. All its terms are zero.

This linear programming problem could be defined in many other ways, but this is the definition used in the MATLAB function ”linprog”, which was the tool used to solve this optimization problem in the algorithm.

### Create, Activate and Synchronize Islands

After the faulty element is detected and the corresponding zones are isolated from the rest of the network, the next step is to determine which zone could work in island mode. This would mean, that the zone's demand is supplied entirely by the DG inside it. If a zone wants to operate in island mode, the equation 3.5 must be fulfilled, where $N$ is the number of nodes in the zone, $P_i$ is the active power demanded by the node $i$, $G$ is the number of distributed generators inside the zone, and $P_k$ is the nominal active power of generator $k$.

$$\sum_{i=1}^{N} P_i \leq \sum_{k=1}^{G} P_k \tag{3.5}$$

If the zone is able to operate in island mode, the corresponding reclosers must automatically isolate the corresponding zone and the DG inside it must be reconnected with the proper procedure. The needed data to designate those breakers that must receive tripping signals is available in database.

Until the fault is not fixed, some of the zones will be entirely supplied by the main source, some will operate in island mode and the rest will face a power outage. After the fault is fixed, the restoration process will ensure that all the zones are entirely supplied through the main source and its DG. The synchronization process is shown in figure 3.6.

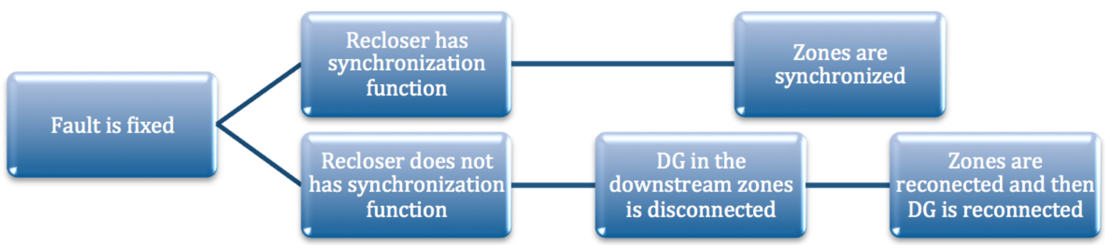



Figure 3.6: Synchronization Process.

# Chapter 4

# Application in a Distribution System

The proposed procedure will be tested in two different circuits. The first one will be based on a small radial system devised by myself to assess the functionality of the implemented algorithms and debug possible errors. In the second stage, the same procedure is going to be developed, but in a more complex IEEE standard circuit.

## 4.1 First Stage: Simple Radial System

The system in this first stage comprises 6 nodes, one for the main generator and the other five that represent zones divided by "smart reclosers". In this case, each node is a zone to evaluate the functionality of the algorithm and debug possible errors. The system topology is shown in figure 4.1 and its data is given in annex B.

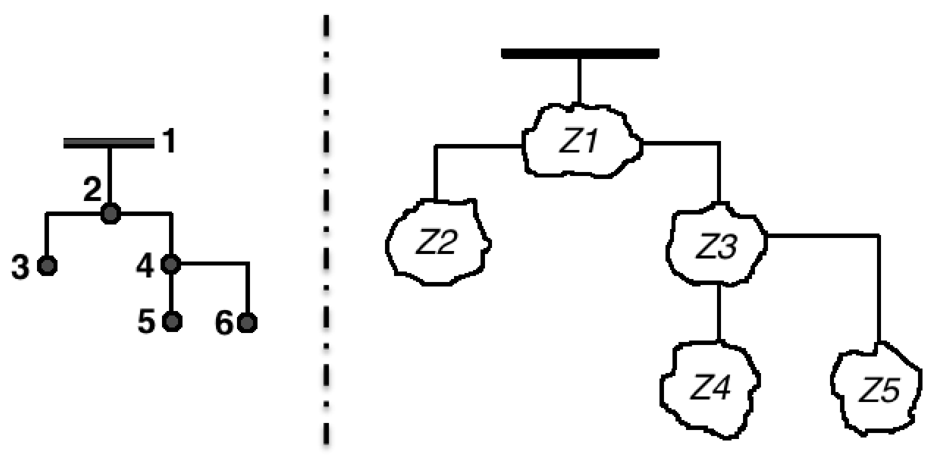



Figure 4.1: Circuit for tests in the first stage.

Initially, this system was used to prove different modules of the algorithm. For example, the values obtained in the short circuit analysis were compared with ETAP results as a validation procedure. Later, multiple simulations were carried out, using ETAP, in order to prove the correct coordination of protection devices.

Below, one of the simulations is shown to observe the performance of the algorithm using the system in figure 4.1. In this example, is going to be seen the response of the system when a distributed generator is included or when a fault occurs as well as the restoration process.

### Example

1. When the system is loaded in the tool, the initial coordination parameters are computed and the initial state is displayed. In the figure 4.2, this information is shown as well as the sequence of operation of the relays, for three different faults, that were obtained using ETAP. In this case, all the zones are operating in normal conditions.

| Zone | ¿Operating? | ¿Island Mode? |
|---|---|---|
| 1 | 1 | 0 |
| 2 | 1 | 0 |
| 3 | 1 | 0 |
| 4 | 1 | 0 |
| 5 | 1 | 0 |

| Relay | TMS |
|---|---|
| 1 | 0.26 |
| 2 | 0.11 |
| 3 | 0.21 |
| 4 | 0.11 |
| 5 | 0.11 |

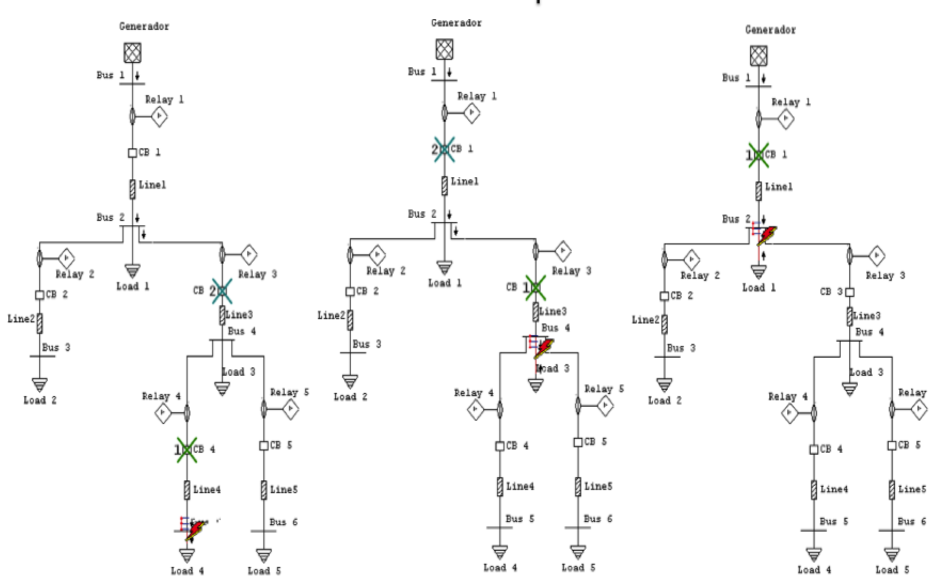



Figure 4.2: Initial state of the simple radial system.

2. When a distributed generator is included in the node 5, the system topology is altered. For the new conditions, the information given by the tool and the sequence of operation of the reclosers for such TMS values, are shown in figure 4.3. All the zones remain operating in normal conditions, but coordination parameters have changed.

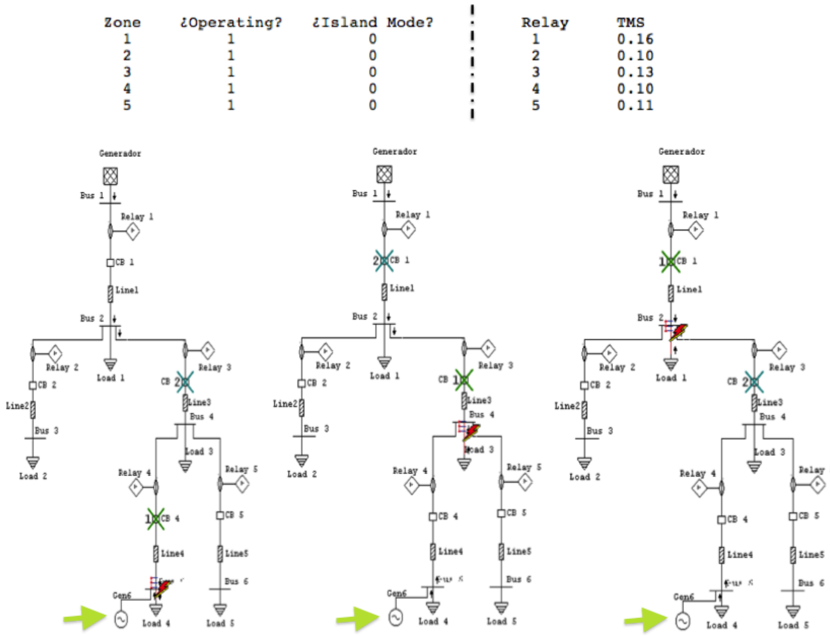



Figure 4.3: State of the 6 nodes radial system, after including DG in the bus 5.

3. Now, a contingency condition is evaluated causing a permanent fault in the branch between nodes 2 and 4. The tool shows the next messages after the fault is caused.

    - *The reconnection function has been activated and the fault has not been cleared.*
    - *Action of the corresponding recloser and communications duty.*
    - *DG inside the isolated zones has been disconnected.*
    - *The following zones are without supply of power: 3, 4 and 5.*
    - *Possibility of island operation is assessed.*
    - *Zone 4 is able to operate in island mode.*
    - *Zone has been completely isolated, DG has been reconnected.*
    - *Zone 4 is now supplied by DG inside it.*

    In the figure 4.4, the state of the system after the fault is shown. Is important to see the TMS values given by the tool, which are zero for the relays of the zones that are not supplied by the main source.

4. After the fault is fixed, the restoration process begins. In this case, the breaker 3 can be closed immediately to restore energy supply in zones 3 and 5. On the other hand, zone 4 has to be synchronized with the rest of the system, as shown in figure 4.5 . If the recloser does not have synchronizer, the DG in the zone has to be disconnected and

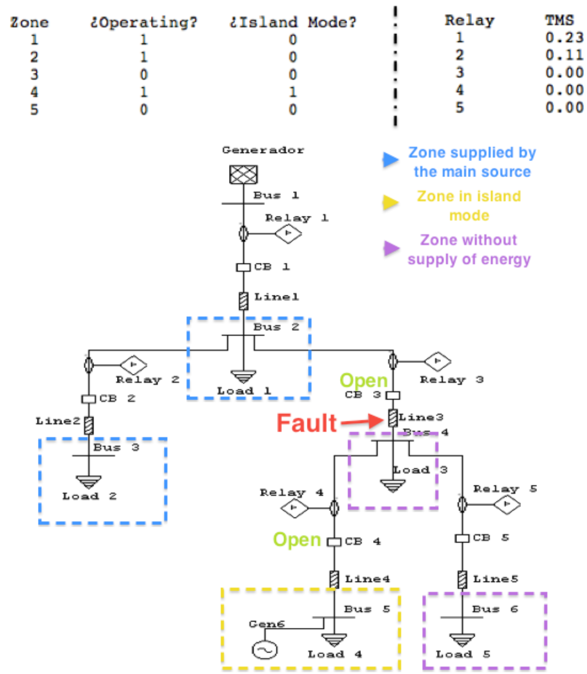



Figure 4.4: State of the system after a fault occurs in the branch between nodes 2 and 4.

then reconnected when the breaker 4 is already closed. The state of the system, after the restoration process, is the same as in the figure 4.3. The messages given by the tool are shown below.

- *Fault has been fixed.*
- *Zones have been properly reconnected and synchronized.*
- *In the following zones, the energy supply has been restored: 3, 4 and 5.*
- *The following zones have ceased to operate in island: 4.*

In the previous example, the proposed procedure of fault management has been tested in a simple radial system for the type of changes considered. The system is meeting its adaptive philosophy, achieving to increase reliability of the system with the island mode operation. The next step would be to prove this procedure in a more complex system, where each zone comprises more than one node.

## 4.2 Second Stage: IEEE 37 Node Test Feeder

In the second stage, a modified version of the IEEE 37 node test feeder is going to be implemented in order to observe some other features of the proposed procedure. The modified

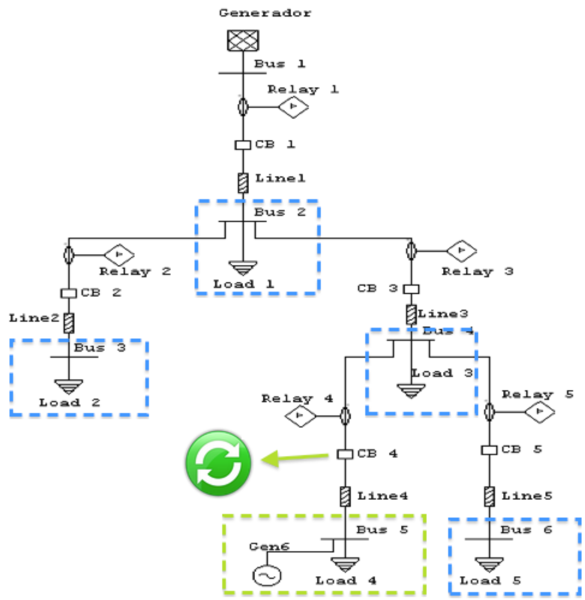



Figure 4.5: Restoration of the system.

version eliminates one node with a transformer, eliminates the voltage regulator and assumes a balancing load. The figure 4.6 shows the mentioned circuit, the necessary information about the system is found in annex C.

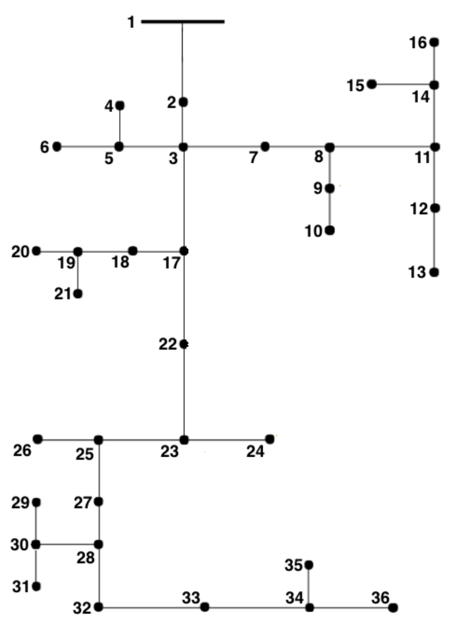



Figure 4.6: Standard Circuit for tests in the second stage.

In this stage, the idea is not only to show the procedure in a more complex circuit, but also to show the initial zoning of the system, which is essential for the implementation of the proposed procedure. This zoning methodology is based on an initial topology condition of the system, focused in the DG capacity and location. In this case, is going to be assumed the existence of three distributed generators. A 500kW generator in the bus 36, a 400kW generator in the bus 12 and a 150kW generator in the bus 31.

Following the zoning methodology enunciated, the system is divided into 6 zones as shown in figure 4.7. Finally, there were two zones designated by its DG capacity and location and four zones created due to topology characteristics and possible future DG penetration. It is important to note that the zoning procedure only takes into account the balance of active power, assuming that all the generators are able to supply the reactive power needed.

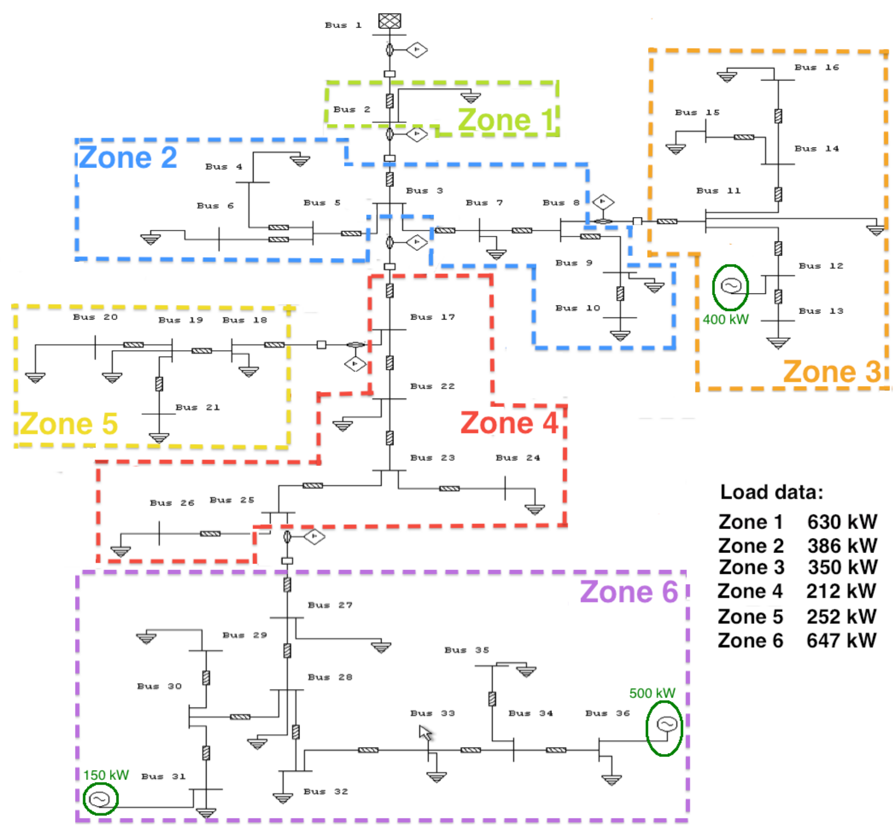
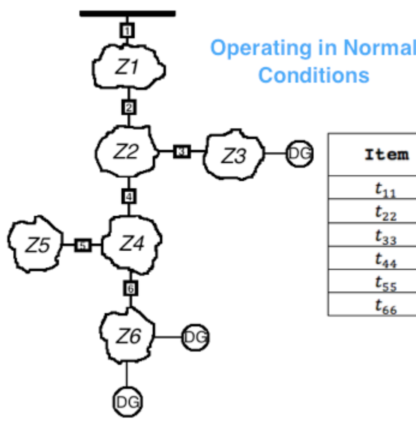



Figure 4.7: Zoning of the system for implementing the fault management procedure.

## Example

Now, is going to be presented a simple example of the procedure in the IEEE stadard system using the zoning shown in figure 4.7. The sequence of operation obtained in ETAP is not given here due to the image size of the system, instead, a table with the operation times and TMS values is going to be presented. In each step, a figure is shown to easily see the state of the system.

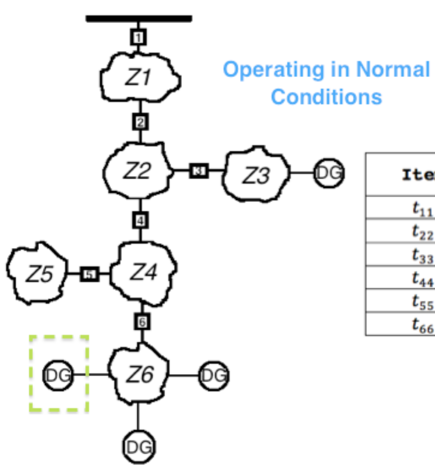
1. The system is loaded in the tool. In the figure 4.8, is presented the initial state of the system and the configuration parameters of the protection devices with the corresponding operating times.




| Item | TMS | Operation time [sec] | Backup times [sec] |
|---|---|---|---|
| $t_{11}$ | 0.38 | 0.5974 | $t_{12}$=0.8845 |
| $t_{22}$ | 0.32 | 0.4618 | $t_{23}$=0.6532 |
| $t_{33}$ | 0.11 | 0.1369 | --- |
| $t_{44}$ | 0.28 | 0.3120 | $t_{45}$=0.6230 |
| $t_{55}$ | 0.11 | 0.1219 | --- |
| $t_{66}$ | 0.11 | 0.1461 | --- |

Figure 4.8: Initial State of the modified circuit IEEE standard.

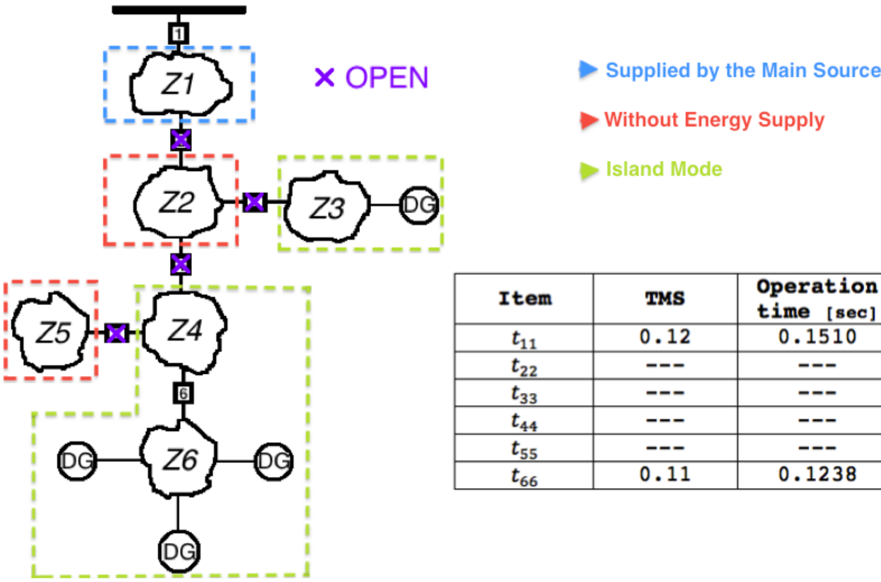
2. A distributed generator of 300kW is included in the bus 33 (Zone 6). The system remains operating in normal conditions and its protection devices have been adjusted.




| Item | TMS | Operation time [sec] | Backup times [sec] |
|---|---|---|---|
| $t_{11}$ | 0.31 | 0.4714 | $t_{12}$=0.7845 |
| $t_{22}$ | 0.22 | 0.3310 | $t_{23}$=0.6392 |
| $t_{33}$ | 0.10 | 0.1369 | --- |
| $t_{44}$ | 0.18 | 0.2720 | $t_{45}$=0.6070 |
| $t_{55}$ | 0.11 | 0.1419 | --- |
| $t_{66}$ | 0.10 | 0.1261 | --- |

Figure 4.9: State of the modified circuit IEEE standard with DG included in zone 6.

3. A fault is caused in the branch between nodes 2 and 3. In figure 4.10, the state of the system, after the fault, is displayed. Is important to note that zones 4 and 6 are operating in island mode and zone 4 does not have any DG. This means that all the load of zone 4 is being supplied by DG in zone 6.




| Item | TMS | Operation time [sec] | Backup times [sec] |
|---|---|---|---|
| $t_{11}$ | 0.12 | 0.1510 | --- |
| $t_{22}$ | --- | --- | --- |
| $t_{33}$ | --- | --- | --- |
| $t_{44}$ | --- | --- | --- |
| $t_{55}$ | --- | --- | --- |
| $t_{66}$ | 0.11 | 0.1238 | --- |

Figure 4.10: State of the IEEE standard circuit after a fault between the nodes 2 and 3.

4. After the fault is fixed, some zones must be synchronized to restore the normal operating condition of the system. This is displayed in figure 4.11.

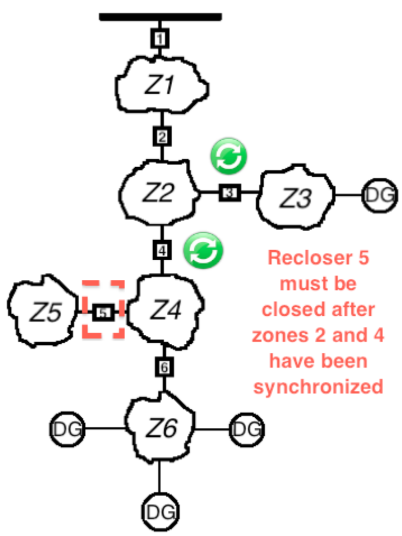



Figure 4.11: Restoration of the IEEE standard circuit.

In the last example, other features of the fault management procedure were presented. Is important to highlight that the location of the recloser cannot be changed, but the system should be able to detect when a zone could be supplied by the DG in another zone. This will be a very important issue to increase reliability in the system.

# Chapter 5

# Discussion

The procedure proposed in this text, states an alternative to face the challenges in fault management of radial systems, caused by the incorporation of distributed generation. The use of this protection philosophy is necessary, in the mid-term, to ensure the correct operation of distribution systems. In this dissertation, it has been understood the main issues that cause the wrong operation of protection devices in radial systems whit DG, and based on this, the procedure was stated. This procedure not only involves the required adjustments to protective devices, but also takes into account some necessary actions to improve the reliability of the system, taking advantage of the DG inside it.

For simulation purposes, the reconfiguration process is based on power flows and computational calculations of short-circuit currents. However, this is not possible for the real time operation of the system. In such case, both load currents and fault currents will be taken from measurements of the system, and the computation of the TMS values will be made, in a short period, after the fault has occurred. This strategy assumes that in this period will not occur a fault.

The proposed architecture for the protection scheme, assumes the use of "smart recloser" with a bunch of features. A methodology was proposed for the location of these reclosers; however, the number of reclosers and its location will be strongly influenced by economic factors. Moreover, one of the most important assumptions in this architecture is a reliable and fast communication process between its devices, which is perhaps one of the main obstacles today for this type of architectures. As future work, it can be observed: the possibility to enhance algorithm for overcurrent relays coordination and minimize the required time to adjust devices, the coordination of the proposed overcurrent protection system with other protection devices and the detailed design of the communication system, among others.

# Chapter 6

# Conclusions

- The proposed procedure of fault management, allows radial systems with DG to face the protection issues and gives some steps to increase reliability of the system, by taking advantage of the DG inside it.
- All the objectives stated were fully met; the procedure was stated, giving the required steps to detect faults, isolate the faulty zone, detect and create possible islands, and restore the energy supply of the entire system. An interactive tool was implemented to show and simulate the procedure of fault management. The devices adjustment task was stated as a linear programming problem and incorporated in the developed tool.
- The tool implemented can be very useful to understand the behavior of radial systems when its topology is changed. It is very easy to use and allows in an very interactive way to make changes in topology and ask for relevant information about the state of the system.
- The methodologies proposed in this dissertation are based on a simulation environment. If it is desired to implement this in a real distribution system, other considerations must be taken into account as mentioned in the discussion chapter.

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# Annex A

### Fault Management Procedure Tool-Handbook

The objective of this tool is to show the procedure of fault management, in distribution system with DG, in a very interactive way. The tool was developed on the software MATLAB using some features of the tool MATPOWER to run the power flows needed. In order to use this tool, the system has to be implemented in the MATPOWER format with some modifications. Below, each one of the columns of each matrix in the format is described.

```
Bus Data Format:
       1   Bus number (positive integer)
       2   Bus type
               PQ bus               = 1
               PV bus               = 2
               Reference bus    = 3
               Isolated bus       = 4
       3   Pd, real power demand (MW)
       4   Qd, reactive power demand (MVAr)
       5   Gs, shunt conductance (MW demanded at V = 1.0 p.u.)
       6   Bs, shunt susceptance (MVAr injected at V = 1.0 p.u.)
       7   Area number, (positive integer)
       8   Vm, voltage magnitude (p.u.)
       9   Va, voltage angle (degrees)

       10  baseKV, base voltage (kV)
       11  zone, loss zone (positive integer)
       12  maxVm, maximum voltage magnitude (p.u.)
       13  minVm, minimum voltage magnitude (p.u.)


Generator Data Format:
       1   Bus number
       2   Pg, real power output (MW)
       3   Qg, reactive power output (MVAr)
       4   Qmax, maximum reactive power output (MVAr)
       5   Qmin, minimum reactive power output (MVAr)
```

```
        6   Vg, voltage magnitude setpoint (p.u.)
        7   mBase, total MVA base of this machine, defaults to baseMVA
        8   status,  >  0 - machine in service, <= 0 - machine out of service
        9   Pmax, maximum real power output (MW)
        10  Pmin, minimum real power output (MW)


 Branch Data Format:
        1   f, from bus number
        2   t, to bus number
        3   r, resistance (p.u.)
        4   x, reactance (p.u.)
        5   b, total line charging susceptance (p.u.)
        6   rateA, MVA rating A (long term rating)
        7   rateB, MVA rating B (short term rating)
        8   rateC, MVA rating C (emergency rating)
        9   ratio, transformer off nominal turns ratio ( = 0 for lines )
        10  angle, transformer phase shift angle (degrees), positive => delay
        11  initial branch status, 1 - in service, 0 - out of service


Generator Short-Circuit data format:
       1   Bus number
       2   Type of connection
       3   Xd, Direct-Axis Reactance
       4   Xd', Transient Reactance
       5   Sub-transient Reactance
       6   r2, Negative sequence resistance
       7   x2, Negative sequence reactance
       8   r0, Zero sequence resistance
       9   x0, Zero sequence reactance
       10   rpt, Grounding resistance
       11   xpt, Grounding reactance
```

When the tool is started, the system's file name is required. After entering this name, the next information and menu is displayed.

```
        Adaptive Protections Tool for Distribution Systems with DG
                  Realized by: Andres F. Botero Valencia
                Graduation Project, Electrical Engineering
                Bogotá D.C, Universidad de los Andes, 2012

     ________________________________________________________________

     ACTUAL STATE OF THE SYSTEM:

                   Zone    ¿Operating?   ¿Island Mode?
                    1          1              0
                    2          1              0
                    3          1              0
                    4          1              0
                    5          1              0
     ________________________________________________________________

                        Relay      TMS
                          1        0.26
                          2        0.11
                          3        0.21
                          4        0.11
                          5        0.11
     ________________________________________________________________

----------------------------------------
MAIN MENU
----------------------------------------
[1] Information of the System
[2] Cause a Fault
[3] Fix a Fault
[4] Include a New Distributed Generator
[5] Elimintae a Distributed Generator
[6] Exit
-----------------------------------------

Type the option number: |
```

Figure 1: Tool Interface.

The rest of the information needed to use the tool, is given with messages when an option is chosen. Below, the parameters used for the predetermined generators are presented. These parameters were calculated based on an ABB technical report (OTTELIN,T 2006 - Machines-Technical Specifications), and using the equation $Z_{new} = Z_{old.p.u}((V_{old}/V_{new})^2(S_{new}/S_{old}))$.

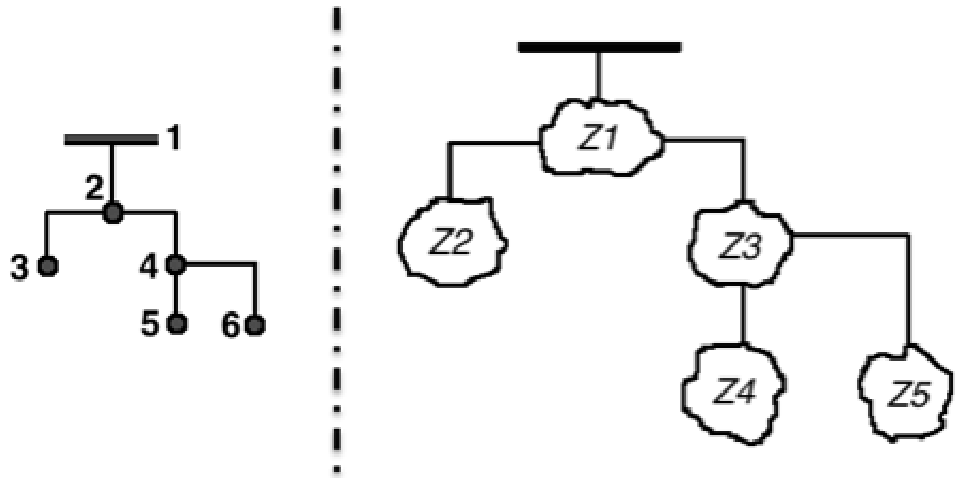
| Machine | 150 kW | 300 kW | 400 kW | 500 kW |
|---|---|---|---|---|
| Xd | 0,4493 | 0,8986 | 1,1982 | 1,8120 |
| Xds' | 0,0756 | 0,1513 | 0,2017 | 0,2521 |
| Xds'' | 0,0439 | 0,0878 | 0,117 | 0,1463 |
| X2 | 0,0466 | 0,0932 | 0,1243 | 0,1554 |
| X0 | 0,0275 | 0,055 | 0,0734 | 0,0917 |

Figure 2: Parameters used for DG.

# Annex B

### Simple Radial System Data

Below, the data of the 6 node system is presented.




| Vbase(kV) | 4.8 | Sbase(MVA) | 1 |
|---|---|---|---|

**Bus Information**

| Bus | Voltage (kV) | Generation | | Load | | | |
|---|---|---|---|---|---|---|---|
| | | Pmax(kW) | Q(kVar) | P(kW) | Q(kVAr) | P p.u | Q p.u |
| 1 | 4,8 | 800 | 500 | 0 | 0 | 0 | 0 |
| 2 | 4,8 | 0 | 0 | 85 | 40 | 0,085 | 0,04 |
| 3 | 4,8 | 0 | 0 | 126 | 63 | 0,126 | 0,063 |
| 4 | 4,8 | 0 | 0 | 93 | 44 | 0,093 | 0,044 |
| 5 | 4,8 | 0 | 0 | 38 | 18 | 0,038 | 0,018 |
| 6 | 4,8 | 0 | 0 | 140 | 70 | 0,14 | 0,07 |
| | | | Total | 482 | 235 | 0,482 | 0,235 |

**Lines Parameters**

| Line | From Bus | To Bus | R p.u | X p.u | B p.u |
|---|---|---|---|---|---|
| 1 | 1 | 2 | 0,00375 | 0,00235 | 0,00054 |
| 2 | 2 | 3 | 0,00689 | 0,00255 | 0,00011 |
| 3 | 2 | 4 | 0,00383 | 0,00199 | 0,00012 |
| 4 | 4 | 5 | 0,00516 | 0,00323 | 0,00074 |
| 5 | 4 | 6 | 0,00413 | 0,00153 | 0,00006 |

Figure 3: Simple Radial System Data.

# Annex C

### IEEE 37 Node Test Feeder

Below, the data of the modified version IEEE 37 Node Test Feeder is presented.

| Bus Information | | |
|---|---|---|
| Nodo | P(p.u) | Q(p.u) |
| 2 | 0,63 | 0,315 |
| 4 | 0,085 | 0,04 |
| 7 | 0,085 | 0,04 |
| 9 | 0,038 | 0,018 |
| 10 | 0,085 | 0,04 |
| 11 | 0,085 | 0,04 |
| 15 | 0,161 | 0,08 |
| 16 | 0,042 | 0,021 |
| 13 | 0,042 | 0,021 |
| 18 | 0,042 | 0,021 |
| 21 | 0,126 | 0,063 |
| 20 | 0,042 | 0,021 |
| 22 | 0,085 | 0,04 |
| 24 | 0,085 | 0,04 |
| 26 | 0,042 | 0,021 |
| 27 | 0,085 | 0,04 |
| 28 | 0,042 | 0,021 |
| 31 | 0,085 | 0,04 |
| 29 | 0,042 | 0,021 |
| 32 | 0,14 | 0,07 |
| 33 | 0,126 | 0,062 |
| 35 | 0,085 | 0,04 |
| 36 | 0,042 | 0,021 |
| 6 | 0,093 | 0,044 |
| 19 | 0,042 | 0,021 |
| Total: | 2,457 | 1,201 |

| # | Lines Parameters | | | | |
|---|---|---|---|---|---|
| | From Bus | To Bus | R p.u | X p.u | B p.u |
| 1 | 1 | 2 | 0,00445 | 0,00300 | 0,00129 |
| 2 | 2 | 3 | 0,00375 | 0,00235 | 0,00054 |
| 3 | 3 | 5 | 0,00689 | 0,00255 | 0,00011 |
| 4 | 5 | 4 | 0,00413 | 0,00153 | 0,00006 |
| 5 | 4 | 6 | 0,00551 | 0,00204 | 0,00008 |
| 6 | 3 | 7 | 0,00383 | 0,00199 | 0,00012 |
| 7 | 7 | 8 | 0,00553 | 0,00287 | 0,00017 |
| 8 | 8 | 9 | 0,00138 | 0,00051 | 0,00002 |
| 9 | 9 | 10 | 0,00896 | 0,00332 | 0,00014 |
| 10 | 8 | 11 | 0,00851 | 0,00441 | 0,00026 |
| 11 | 11 | 12 | 0,00638 | 0,00331 | 0,00020 |
| 12 | 12 | 13 | 0,00482 | 0,00179 | 0,00007 |
| 13 | 11 | 14 | 0,01585 | 0,00587 | 0,00024 |
| 14 | 14 | 15 | 0,00207 | 0,00077 | 0,00003 |
| 15 | 14 | 16 | 0,01309 | 0,00485 | 0,00020 |
| 16 | 3 | 17 | 0,00516 | 0,00323 | 0,00074 |
| 17 | 17 | 18 | 0,00413 | 0,00153 | 0,00006 |
| 18 | 18 | 19 | 0,00298 | 0,00155 | 0,00009 |
| 19 | 19 | 20 | 0,00482 | 0,00179 | 0,00007 |
| 20 | 19 | 21 | 0,00344 | 0,00128 | 0,00005 |
| 21 | 17 | 22 | 0,00638 | 0,00331 | 0,00020 |
| 22 | 22 | 23 | 0,00213 | 0,00110 | 0,00007 |
| 23 | 23 | 24 | 0,00638 | 0,00331 | 0,00020 |
| 24 | 23 | 25 | 0,00340 | 0,00177 | 0,00010 |
| 25 | 25 | 26 | 0,00551 | 0,00204 | 0,00008 |
| 26 | 25 | 27 | 0,00340 | 0,00177 | 0,00010 |
| 27 | 27 | 28 | 0,00595 | 0,00309 | 0,00018 |
| 28 | 28 | 30 | 0,00896 | 0,00332 | 0,00014 |
| 29 | 30 | 29 | 0,02205 | 0,00816 | 0,00034 |
| 30 | 30 | 31 | 0,00344 | 0,00128 | 0,00005 |
| 31 | 28 | 32 | 0,00681 | 0,00353 | 0,00021 |
| 32 | 32 | 33 | 0,00425 | 0,00221 | 0,00013 |
| 33 | 33 | 34 | 0,00425 | 0,00221 | 0,00013 |
| 34 | 34 | 35 | 0,00344 | 0,00128 | 0,00005 |
| 35 | 34 | 36 | 0,00425 | 0,00221 | 0,00013 |

Figure 4: IEEE 37 Node Test Feeder Data.

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Procedure of Fault Management in Distribution Networks with Distributed Generation

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Número de páginas: 44

Ilustraciones: 29

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