Universidad de los Andes

Engineering Faculty

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An Adaptive Multi-Agent Approach to Protection Systems in Distribution Circuits with Distributed Generation

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Content

Chapter 1

Introduction

Several Artificial Intelligence (AI) techniques have been proposed to solve problems that need autonomous behavior in order to achieve a specific objective. This branch of computer science has tried to imitate the step-by-step reasoning that humans use when they solve a problem, and nowadays researchers have developed highly successful methods for dealing with a wide range of topics that goes from financial issues [19] to medical concerns [7], demonstrating its suitability to almost any challenge that is presented to humans.

One of the areas in which AI techniques have been proposed to solve problems is the electrical energy field. Electrical power systems have been enlarged to supply a growing demand of electrical energy; therefore they have become more interconnected and difficult to operate. Hence, the tasks of planning, operating, and protecting these systems cannot be performed any more in a traditional way. That is why we can think of introducing some of the AI techniques used, such as neural networks [17], genetic algorithms [25], and fuzzy logic [36], among others. Electrical protections management is one of the most interesting tasks in this field for the application of artificial intelligence techniques, due to the new trend toward systems that are more energy efficient, reliable, and environmentally friendly; bringing up topics such as distributed generation. This trend brings new technical challenges in engineering and especially in protection schemes that must be capable to adapt themselves to the continuous changes in its topology, in order to keep the basic criteria of sensitivity, selectivity, and velocity demanded by a coordinated protection system.

Multi-agent systems meet all the characteristics required by this new kind of electrical protections, such as self-coordination, organization, cooperation, and communication [35]. The justification for using agents lies in its inherent features of flexibility, autonomy, reactivity, pro-activeness, social ability, its distributed nature, and its fault tolerance. In such case, protective relays and associated equipment are seen as agents that can interact in order to meet a specific target, decrease the impact of electrical faults in power systems. By doing so, the system would not be more centrally controlled and would be capable of managing distributed conditions. One of the most important parts in such system would be the decision-making process of each agent, which can be accomplished with a large number of techniques. The most used techniques in electrical power systems are shown in [18] [29]. However, there are other techniques less explored that could be very useful for such systems, as mentioned in [31] where a bee behavior based technique is shown to have very useful features in the relay coordination task.

Some investigations in MAS related to power engineering have shown successfully the implementation of such systems. One of this is an agent implementation for micro-grids control, checked successfully on a test electrical network and developed at the National Technical University of Athens (NTUA) [9]. Also, in the University of Strathclyde, a system called Protection Engineering Diagnostic Agents (PEDA) [8] has been developed. This last system has been successfully implemented in an electrical system, demonstrating that the real application of such systems is achievable. The success of these systems has led to the creation of organizations that promotes agent-based technologies and the interoperability of its standards with other technologies (e.g., Foundation for Intelligent Physical Agents (FIPA)). There are other new very interesting explorations into the use of agent technology applied to the protection coordination of power systems in [34] [12] [33], among others. On the other hand, recently, some intelligent methods have been proposed for coordination of relay problems. These developments were based on observations of the social behavior of animals such as bird flocking, fish schooling and swarm theory. In [26], a genetic algorithm (GA) is applied to the coordination problem to reach the global optimum value and is compared with conventional single point searching methods. Others like [22], have tried to assess the implementation of artificial intelligence techniques based on bees behavior for optimal coordination of overcurrent relays. Its purpose is to find an optimum relay setting to minimize the time of operation of relays and at the same time, to avoid the wrong operation of relays.

As mentioned, the unstoppable grow of electrical demand and the complexity of managing such systems is essential in the development of new techniques, mainly in the protection schemes, as the functionality and reliability of the system depends on it. Hence, this work assesses how a multi-agent system application can be used in electrical protections and state a conceptual architecture o f the system. Furthermore, two different techniques for decision-making process are compared, i.e, two honey bee social algorithms based on [21] and [16], and a linear programming representation of the problem. At the end, this work will show us the use of such techniques in distribution systems and a simulation tool that shows the expected behavior of the multi-agent system is developed. In order to see the expected behavior of the system will be used the standard IEEE 37 node test feeder.

Chapter 2

Background

Modern design of power systems provides different strategies to decrease probability of faults, however is economically and physically improbable to remove them totally. This is why an appropriate reaction to the occurrence of faults becomes completely necessary in order to mitigate its effects on the system. This reaction cannot be taken any more in a traditional way due to the new challenges in the power system caused by the growing demand of electricity and the onset of new technologies, so novel techniques must be developed. Several AI techniques have been proposed to face the new challenges in power systems, but one of the most interesting options for these challenges are multi-agent systems due to their distributed properties.

2.1 Multi-Agent Systems

Agents were born of the investigation in artificial intelligence (AI). From this, were defined MAS as systems composed by several agents collaborating and interacting to solve an specific problem, which would be difficult or impossible for an individual agent. In order to understand the use of MAS in electrical protections, a definition of ”agent” is necessary. Several definitions have been presented trying to suit their own applications, thus for our purpose we are going to consider the following definition.

Agent: Agents are computational systems that inhabit some complex dynamic environment, sense and act autonomously in this environment, and by doing so realize a set of goals or tasks for which they are designed [5].

In most cases, an agent will not have complete control over its environment, but it will have partial control and through communication with other agents will influence in the whole system behavior. A general sketch of an agent and its interaction with the environment, is shown in figure 2.1.

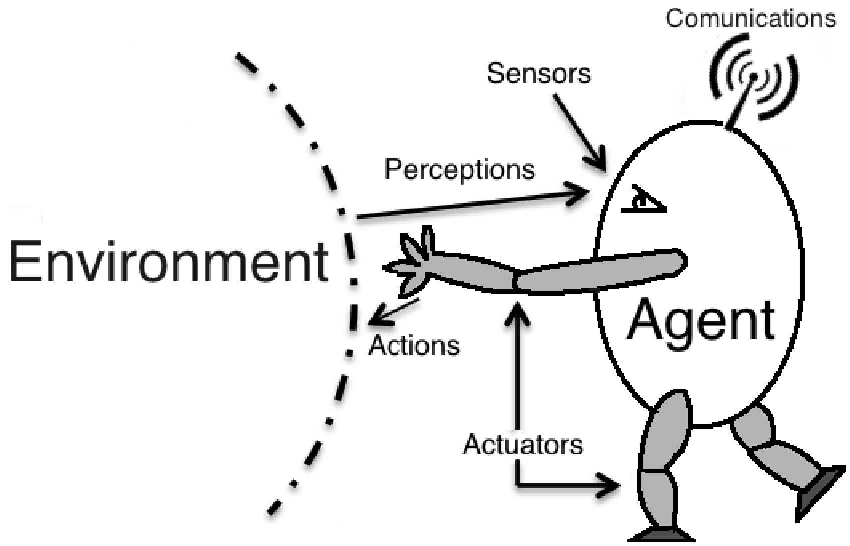


Figure 2.1: General Sketch of an Agent and its interaction with the environment.

In order to be called and intelligent agent, it should have these three main properties [1]:

- **Reactivity:** Intelligent agents are able to perceive their environment, and respond in a timely fashion to changes that occur in it in order to satisfy their design objectives.

- **Pro-activeness:** Intelligent agents are able to exhibit goal-directed behaviour by taking the initiative in order to satisfy their design objectives.

- **Social-ability:** Intelligent agents are capable of interacting with other agents (and possibly humans) in order to satisfy their design objectives.

Besides, an agent could have these other properties: autonomy, initiative, mobility , veracity, benevolence and rationality, but it does not need to possess them all.

Agents are divided in two simple types; purely reactive agents and deliberative agents. The first one refers to agents that respond directly to a specific perception. The second one refers to agents that act based not just on their perceptions, but also in the state of the environment and the past actions. Diagrams of these types of agents are shown in figure 2.2.
The environment can also be described by its properties, these are divided in five pairs of mutually exclusive properties, which are shown below [1].

- **Accessible or Not-accessible:** An accessible environment is one in which the agent can obtain complete, accurate, up-to-date information about the environment's state.

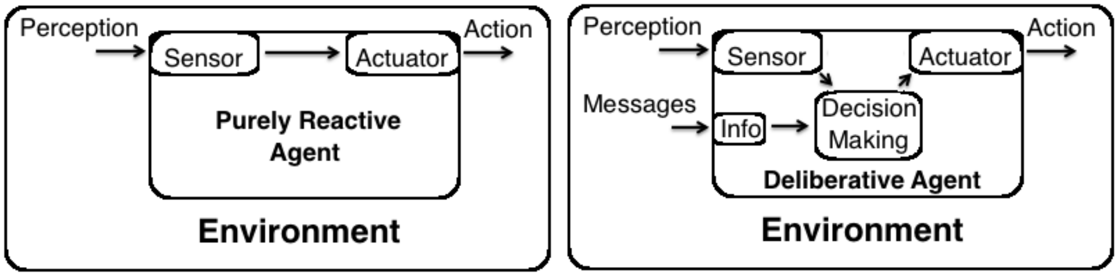


Figure 2.2: Purely reactive agent (Left) and deliberative agent (Right).

- **Deterministic or Non-deterministic:** A deterministic environment is one in which any action has a single guaranteed effect, there is no uncertainty about the state that will result from performing an action.
- **Static or Dynamic:** A static environment is one that can be assumed to remain unchanged except by the performance of actions by the agent. In contrast, a dynamic environment is one that has other processes operating on it, and which hence changes in ways beyond the agent's control.
- **Episodic or Non-episodic:** In an episodic environment the choice of action in each episode depends only on the episode itself.
- **Discrete or Continuous:** An environment is discrete if there are a fixed, finite number of actions and percepts in it.

In most cases an agent will only control a part of the environment, and the main problem facing agents is to decide what action to take in order to meet their objectives.

Bio-Inspired Artificial Intelligence

Traditionally, artificial intelligence has been concerned with reproducing the abilities of human brains; newer approaches take inspiration from a wider range of biological structures that that are capable of autonomous self-organization. Bio-inspired artificial intelligence, on the other hand, takes a more decentralised approach, which often involve the method of specifying a set of simple rules, a set of simple organisms which adhere to those rules, and a method of iteratively applying those rules. Today, these techniques have become an essential part of several areas, providing a relief for many of the most difficult problems in computer science.

One of these techniques, lately applied for several engineering problems is the artificial bee colony algorithm. This, is a swarm based meta-heuristic algorithm for optimizing numerical problems and was introduced by Dervis Karaboga in 2005. It mimics the food foraging behaviour of swarms of honey bees. In its basic version, the algorithm performs a kind of neighbourhood search combined with random search. The model comprises three essential components: employed and unemployed foraging bees, and food sources. These three components are used to define two main modes of beahavior for self organizing and collective intelligence; the recruitment of foragers to rich food sources and the abandonment of poor sources.

2.2 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 2.1 shows the general advantages and disadvantages (Challenges) that brings the incorporation of DG on the current power system.

Table 2.1: Advantages and Disadvantages of DG

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 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 2.3.

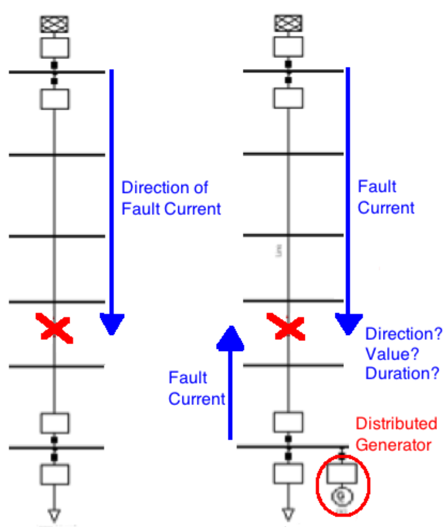


Figure 2.3: System without DG (Left) and with DG (Right).

2.3 Electrical Protections

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 operation 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 occurrence 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 2.4.

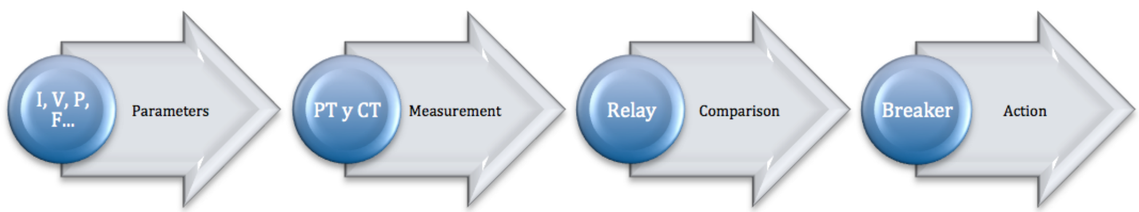


Figure 2.4: Basic process in a ESP when a fault occurs.

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 [11].

- **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.

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.

2.3.1 Faults

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 branches of trees.

Permanent Faults: This kind of failure persist 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 break of lines, falling of support structures and equipment breakdown in the system.

2.3.2 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 [38]. 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.

$$t = \frac{\alpha * TMS}{((I_{Fault}/I_{Pick-up})^{\beta} - 1} \tag{2.1}$$

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 α and β determine the type of curve of the relay's operation, its values are shown in table 2.2.

Table 2.2: Form constants for exponential equation by IEC

Type of Curve	α	β
Standard Inverse	0.14	0.02
Very Inverse	13.5	1
Extremely Inverse	80	2
Large Inverse	120	1

2.3.3 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 recloser its philosophy has been framed by an automatic reaction; however, due to the new challenges presented by power systems, reclosers are evolving to 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 Type SDR Distribution Recloser [23], ABB with its three-phase recloser OVR [2] and Noja Power with the OSM recloser [20]. These and other companies are trying to improve reclosers 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 2.5.

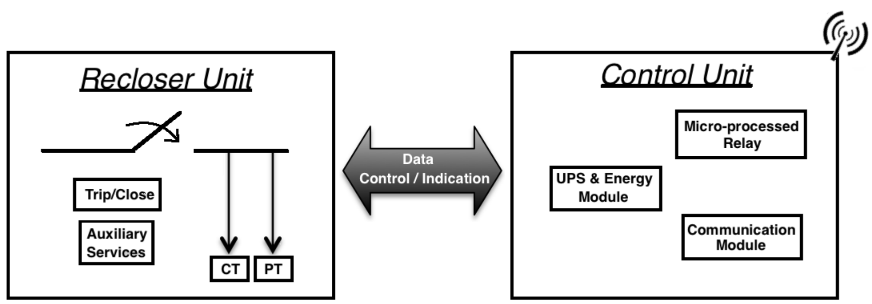


Figure 2.5: Noja Power automatic recloser block diagram. [20]

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.

Some investigations in MAS related to power engineering have shown successfully the implementation of such systems. One of this is an agent implementation for micro-grids control, checked successfully on a test electrical network and developed at the National Technical University of Athens (NTUA) [9]. Also, in the University of Strathclyde, a system called Protection Engineering Diagnostic Agents (PEDA) [8] has been developed. This last system has been successfully implemented in an electrical system, demonstrating that the real application of such systems is achievable. The success of these systems has led to the creation of organizations that promotes agent-based technologies and the interoperability of its standards with other technologies (e.g. Foundation for Intelligent Physical Agents (FIPA)). There are other new very interesting explorations into the use of agent technology applied to the protection coordination of power systems in [34] [12] [33], among others. On the other hand, recently, some intelligent methods have been proposed for coordination of relay problems. These developments were based on observations of the social behavior of animals such as bird flocking, fish schooling and swarm theory. In [26],a genetic algorithm (GA) is applied to the coordination problem to reach the global optimum value and is compared with conventional single point searching methods. Others like [22], have tried to assess the implementation of artificial intelligence techniques based on bees behavior for optimal coordination of overcurrent relays. Its purpose is to find an optimum relay setting to minimize the time of operation of relays and at the same time, to avoid the wrong operation of relays.

A more detailed literature review is presented in annex D.

Table 2.3: State of the art, adaptive protection schemes

References	**Description**
[14],[13], [28], [15]	The proposed schemes in these 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.
[9], [34], [33], [12], [10], [8]	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.
[24], [4], [22], [32]	These references assess the implementation of artificial intelligence techniques for optimal coordination of overcurrent relays, considering the combination of primary and backup relays. Its purpose is to find an optimum relay setting to minimize the time of operation of relays and at the same time, to avoid the wrong operation of relays.
[27], [37], [30]	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 Protection System

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 Distributed Generation (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 it 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 adjustment parameters automatically, based on the operating conditions.

Based on this, a conceptual architecture with the required elements for an adaptive protection system is stated. The protection scheme would be based on an initial operating condition of the system, which is given by certain zones in the system determined mainly by the capacity and location of distributed generators. With this zoning 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 distributed generator 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.

3.1 Multi-Agent System

The aim of the protection scheme 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, it is essential to determine the equipment features that are needed and state an operation philosophy for the protection system. So, after understanding the main issues in electrical protections by introducing DG, the next step is to develop a flowchart that shows the desired behavior of the system, after the occurrence of a fault. The flowchart

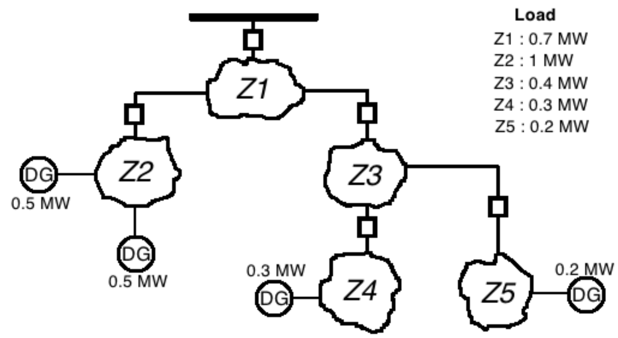


Figure 3.1: Radial distribution system divided into zones according to their DG capacity.

developed 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 figure 3.2.

- **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 island 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.

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 reclosers 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 island 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.

Having in mind that, in proportion, it 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. Now, having stated the desired functionality of the system, the next step is to discriminate

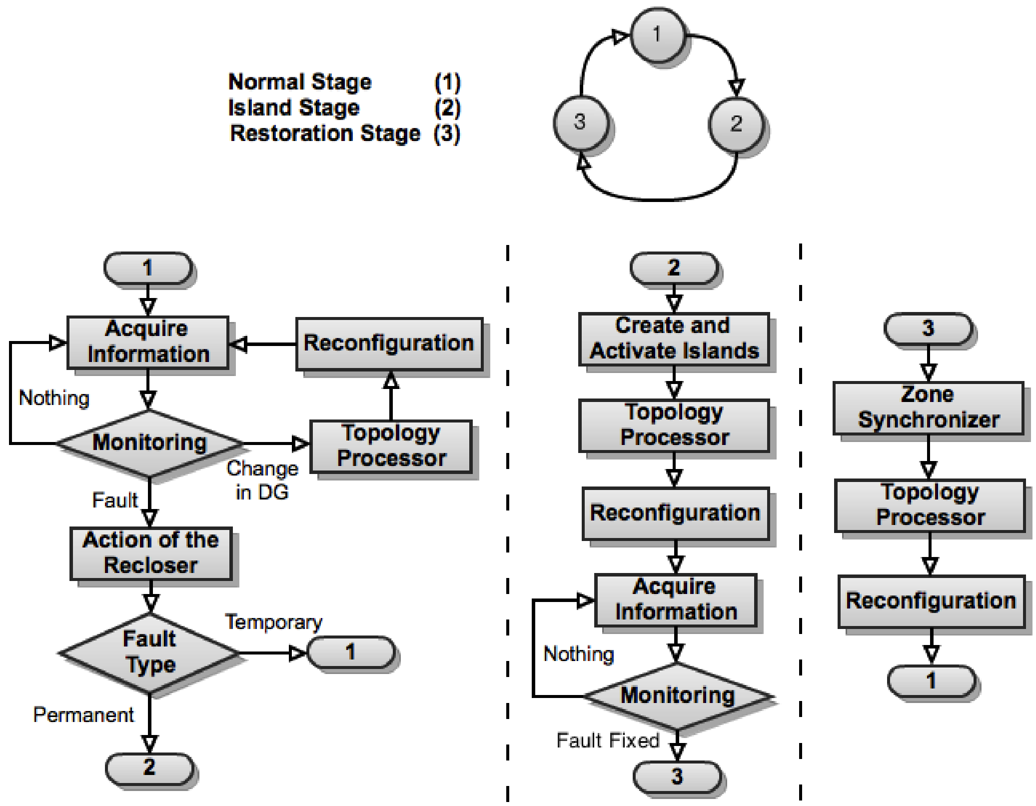


Figure 3.2: Flowchart of the expected behavior of the system after a fault occurs.

the general tasks and the equipments involved in each task. Besides, the type of agent which is going to be responsible of each task is assigned. This is shown in table 3.1.

Table 3.1: General tasks in the system

General Tasks	Equipment Involved	Type of Agent
Acquire Information	CT y PT	Purely Reactive
Monitoring	Relay	Purely Reactive
Reclosure (Switching)	Breaker	Purely Reactive
Topology Processor	Software	Deliberative
Reconfiguring Protective Devices	Software	Deliberative
Create and Activate Islands	Software	Deliberative
Zone Synchronizer	Software	Deliberative

All the actions carried out by deliberative agents will be based on a decision-making process. These tasks will be explained, but only a methodology will be proposed for the reconfiguration task. After this, it is important to define the properties of the environment where the system is going to interact. So, based on the properties that a multi-agent system environment should have and taking into account that in this case the environment is the electric power system, the following properties were defined.

- **Not-accessible** → Each agent cannot obtain complete, accurate, and up-to-date information of the system. However, the environment is going to be assumed accesible in order to show the expected behavior of the system.
- **Deterministic** → Any action has a single guaranteed effect.
- **Non-episodic** → The next episode does depend on the action taken in the previous episodes.
- **Dynamic** → Does not remain unchanged, not only the performance of actions by agents can alter the system.
- **Finite** → There are a fixed number of actions and perceptions in the environment.

A summary of the multi-agent architecture proposed so far, is illustrated in the figure 3.3.

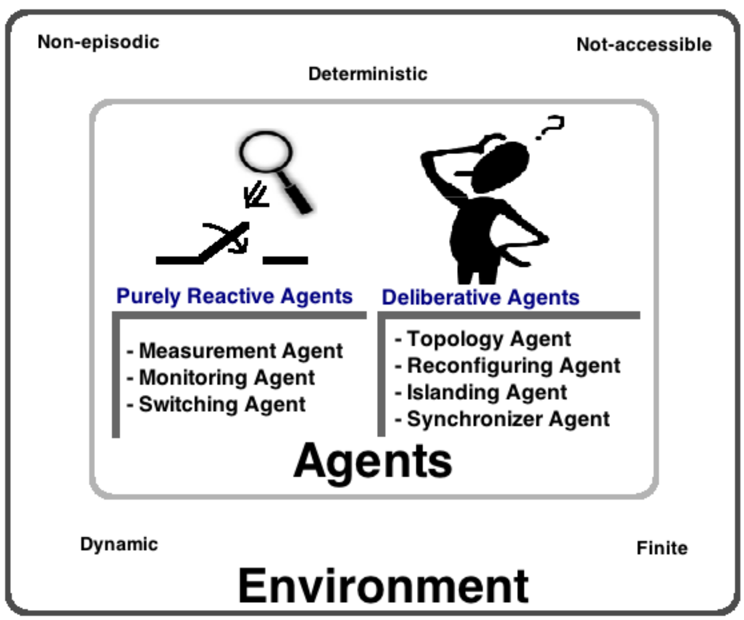


Figure 3.3: General sketch of the multi-agent system.

Now, it is important to give a more detailed description of the main tasks of each agent and their interaction with other agents. In order to preserve the philosophy of the proposed multi-agent system, the architecture of the protection system should be distributed. Figure 3.4 shows a diagram with the conceptual architecture for two recloser units. 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 recloser units.

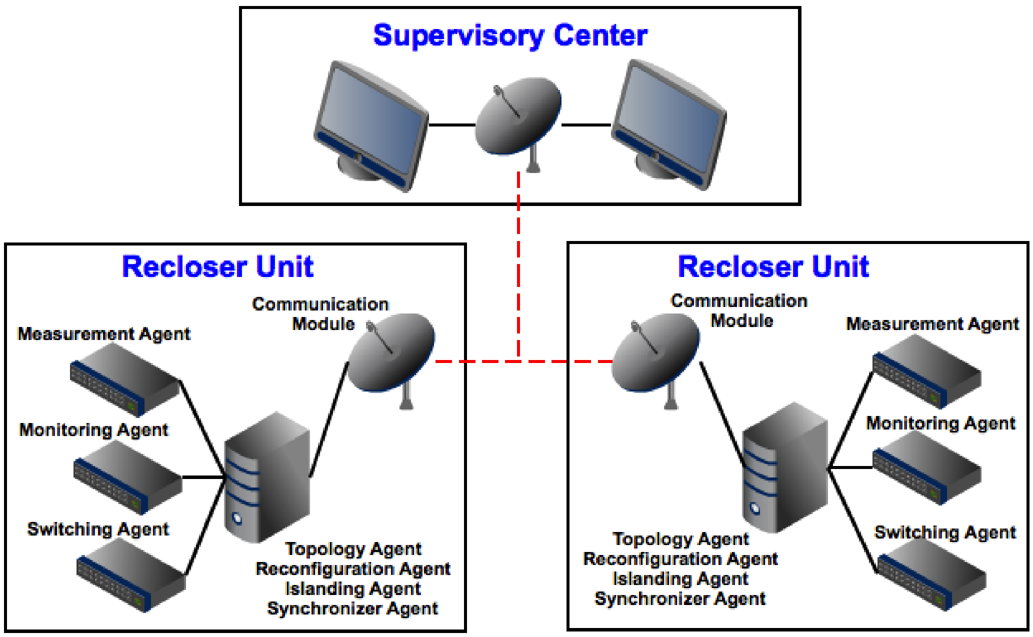


Figure 3.4: Conceptual architecture of the multi-agent system for two recloser units.

Measurement Agent: is responsible for measuring different parameters of the system, mainly the current through the branches where the recloser is located, and then send them to the monitoring agent. Its interaction would be mainly with the monitoring agent.

Monitoring Agent: is responsible for taking the data given by the measurement agent and compare it with some adjusted values. It would send some signals to the switching agent and the topology agent to inform the occurrence of a fault. Its interaction would be mainly with the measurement agent, switching agent, and topology agent.

Switching Agent: as soon as it receives the signal informing the occurrence of a fault, the switching agent is responsible for opening the recloser unit and clearing the fault. Its interaction would be mainly with the monitoring agent.

Topology Agent: is responsible for taking information about topology changes, process it and send information to the reconfiguration agent and islanding agent. Its interaction would be mainly with the monitoring agent, reconfiguring agent.

Reconfiguring Agent: is responsible for computing the new adjustment parameters for the protective devices, based on the information given by the topology agent. Its interaction would be mainly with the topology agent.

Islanding Agent: as soon as the fault is cleared by the switching agent, the islanding agent is responsible for evaluating the possibility of island modes and sending the corresponding signals to the switching agents, in order to isolate the zone. Its interaction would be mainly with the monitoring agent and switching agent.

Synchronizer Agent: after a signal is received informing the solution of a fault, the synchronizer agent begins the restoration process. For this, it would inform properly the switching agent to close the recloser and would send a signal to the topology agent. Its interaction would be mainly with the switching agent and topology agent.

3.2 Reconfiguration Task

As mentioned, some of the agents will have to perform actions based on different issues and not just on perceptions, thus a decision-making process is needed. This decision-making process will be different for each of the tasks performed by deliberative agents. In this case, the decision-making process is focused in the reconfiguration task, as it is responsible for assigning new parameters for the relays when the topology of the system has changed.

The reconfiguration task must be automatic in order to preserve the adaptive philosophy of the proposed multi-agent system. Two different meta-heuristic methods inspired in the forage cycle of a bee colony are proposed to properly coordinate and adjust the overcurrent function of the reclosers between zones. Finally, these methods are compared with a proposed solution for the reconfiguration task that represents the coordination process as a linear programming problem.

3.2.1 Artificial Bee Colony Methods

Given that these techniques are going to be used for the reconfiguration task, the aim of the algorithm will be to minimize the operation time of associated relays in the system. Hence, the objective function will be given by

$$f = W_1 \sum_{i=1}^{N} t_i^2 + W_2 \sum_{i=1}^{M} [\Delta t_{mb} - W_3(\Delta t_{mb} - |\Delta t_{mb}|)]^2 \quad , \quad \Delta t_{mb} = t_b - t_m - CTI \tag{3.1}$$

$$t = \frac{\alpha TMS}{((I_{Fault}/I_{Pick-up})^{\beta} - 1} \quad , \quad I_{pick-up} = 1.5 I_{Load} \tag{3.2}$$

where, W_1 is the weight in the objective function for the operation time of relays, W_2 is the weight in the objective function for the coordination times, and W_3 is the weight of penalty in the objective function for the miscoordination of the relays. The second summation term is exclusively included to ensure the correct coordination of the relays, so when Δt_{mb} is negative OF becomes greater, which means that the total operation time increases.

Thus, since the aim of the algorithm is to minimize a value, a modified honey bee social foraging algorithm for numerical optimization must be implemented. Two different methods are proposed: the first method is based on the honey bee social foraging algorithm proposed in [21] for resource allocation, and the second method is based on the artificial bee colony algorithm for numerical function optimization presented in [16]. Finally, both of the proposed algorithms would be based on the forage cycle of bee colonies, where the sites with nectar are represented with a bunch of solution vectors to the optimization problem, as shown in figure 3.5.

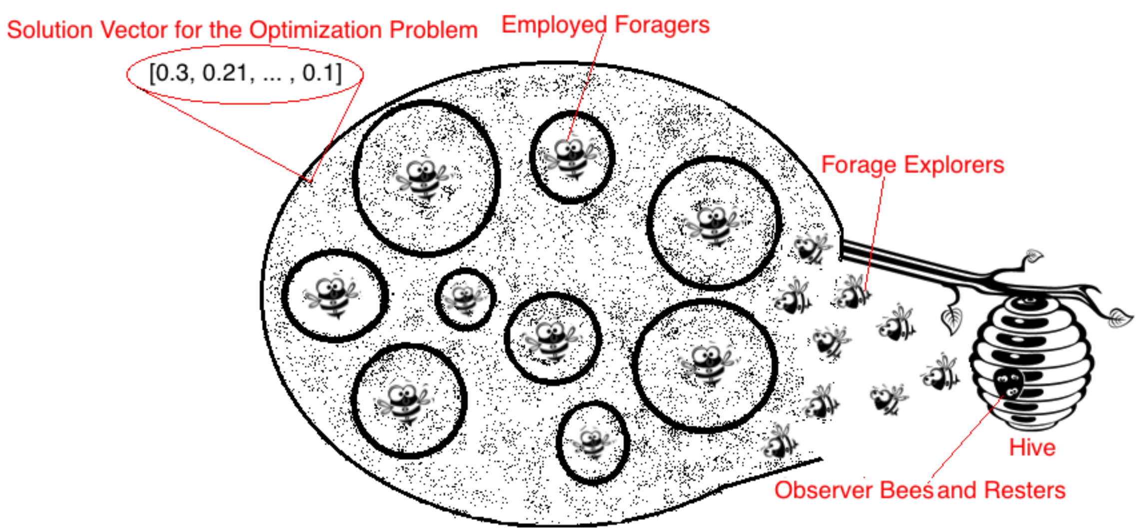


Figure 3.5: Description of the artificial bee colony forage cycle for this application.

First Method

In this method, we assume that there are a fixed number of bees (B) involved in the forage cycle. During the foraging, bees explore a determined landscape with a spatial distribution of sites with different amounts of nectar or food. The colony of artificial bees contains three groups of bees: employed bees, onlookers, and scouts. This last two are considered unemployed bees. The whole process comprises an exploration of the sites and an evaluation of its nectar amounts. Based on this nectar assessment the employed bees can recruit other bees or can become unemployed. In the same way, an scout bee that finds a profitable site becomes an employed bee. Figure 3.6 shows a general flowchart of the foraging cycle for this method.

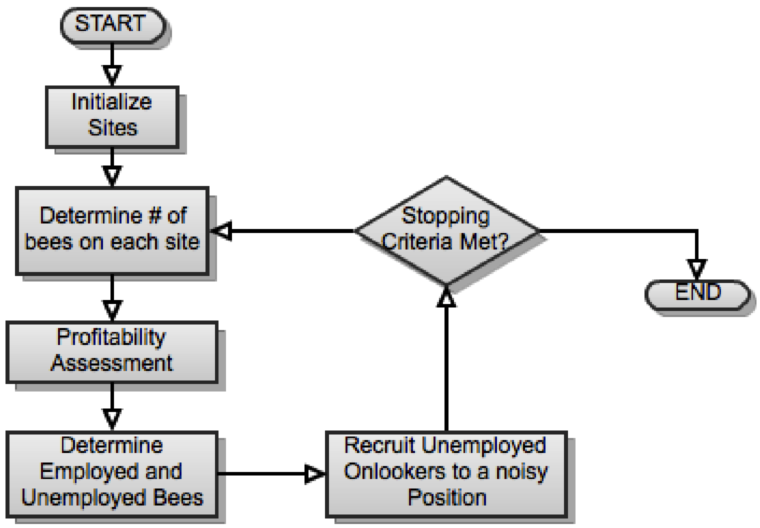


Figure 3.6: General flowchart for the first ABC method.

In order to apply this method on the relays coordination problem, some analogies have to be made. For this modified version, there are two main analogies:

$$\text{The Position of a food source (site)} \iff \text{A possible solution of the optimization problem}$$
$$\text{Nectar amount in a site} \iff \text{Quality or fitness of the associated solution}$$

More specifically, a position of a food source would be represented by a solution vector of the optimization problem with a number of elements equal to the number of relays in the system, each element of the vector is the value of the time multiplier setting (TMS) for each relay. On the other hand, the nectar amount in a site would be given by the quality of the solution that represents the operation time of the protection system with the corresponding adjustment. Unlike the description given in [21], for this optimization application there is not a direct division of sites in the landscape. Hence, we cannot distinguish sites in cylinders with heights proportional to the nectar profitability and radius proportional to sites spread.

Let k be the index of the foraging expedition and assume that at time $k = 1$ one expedition has occurred, and so on. Initially, the number of employed foragers is zero since no foraging sites have been found. Those $B_f(k)$ employed foragers are actively assessing nectar amount and will not follow dances. From the $B_u(k)$ unemployed foragers, there are $B_o(k)$ that observe the dances of employed foragers and $B_r(k)$ that rest. The amount of observers and resters is decided by a rule explained below. Finally, there are $B_e(k)$ forage explorers that go to random positions in the environment and assess its nectar amount but are not dedicated to the site unless they find a relatively good site.

Having in mind that the fitness represents the quality of the solution and the aim is to minimize the objective function, the fitness $J(k)$ of each site for the kth expedition can be expressed in terms of the objective function as

$$J(k) = \frac{1}{1+OF} \tag{3.3}$$

For the kth foraging expedition lets assume that a bee only samples the foraging profitability landscape once. The profitability assessment for each site is given by

$$F(k) = \begin{cases} 1 & \text{if } J(k) \geq 1 \\ J(k) + W(k) & \text{if } 1 > J(k) > \varepsilon \\ 0 & \text{if } J(k) < \varepsilon \end{cases} \tag{3.4}$$

where $W(k)$ represents a noise in such assessment given by an uniformly distributed variable, which represents up to a $\pm 10\%$ error in the assessment of profitability by each employed forager in the kth expedition. Besides, a lower threshold on site profitability is stated as ε.

Based on this profitability assessment, each employed bee takes a decision about dancing. Therefore, if a site profitability $F(k)$ is zero the bee would not decide to dance and becomes an unemployed forager. On the other hand, if $F(k)$ is greater than the lower threshold on site profitability ε, then the bee would decide to dance and its dance strength would be proportional to its profitability. Given this, for each expedition we let $P_o \in [0, 1]$ to denote the probability of becoming and observer for unemployed bees; hence $1-P_o$ will be the probability of becoming a rester. As in [21], we chose $P_o = 0.35$ so that when all bees are unemployed, 35% will explore.

After determining the number of unemployed foragers, we take the $B_o(k)$ observers and for each one, with probability $P_e(k)$ we make it an explorer. This probability, based on [21], is given by

$$P_e(k) = \exp\left(-\frac{1}{2}\frac{G^2(k)}{\sigma^2}\right) \tag{3.5}$$

where $G(k)$ is the sum of the profitabilities of all the $B_f(k)$ employed foragers. Notice that if the total profitability assessment is zero, then $P_e(k) = 1$ and all the observer bees will explore. Hence, if the profitability of the sites is low, the observers are less likely to find a dancer, and so on. In this way, observers are recruited to forage sites with a probability $1 - P_e(k)$. Then, the probability that an observer bee will follow the dance of bee i is defined as

$$P_{oi} = \frac{F_i}{\sum_{i=1}^{B_f(k)} F_i} \tag{3.6}$$

So, the algorithm begins initializing a random population (random solutions to the optimization problem) and initialize 35% of the bees as employed bees, an the rest as explorers. Here, a while loop begins until a stopping criteria is met (number of expeditions). In this loop, the profitability of each site is assessed (quality of each solution is evaluated), and the number of employed bees is determined. Next, the onlooker bees are recruited to each site with the corresponding probability. The new expedition takes into account the recruited bees for each site. Algorithm 1 summarizes, in a pseudo-code, the general aspects of the modified honey bee social foraging algorithm described above.

Second Method

In this method, first half of the colony consists of employed bees and the second half constitutes the observers. For every site, there is only one employed bee, so the number of employed bees is equal to the number of food sources around the hive. The employed bee whose food source is exhausted becomes a scout. When a site is abandoned, a new food source is randomly determined by a scout bee. Figure 3.7 shows a general flowchart of the foraging cycle for this method.

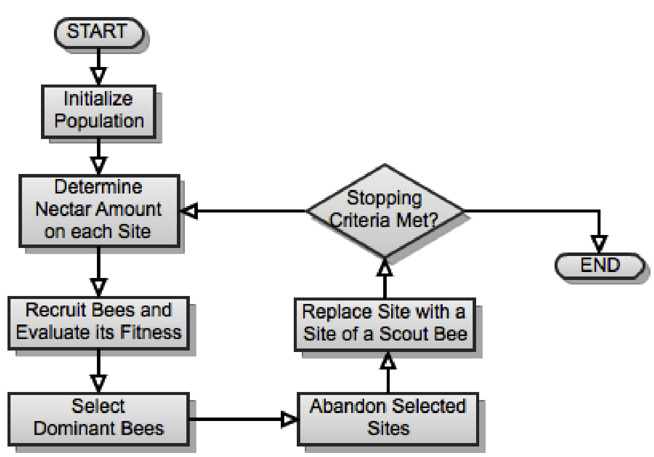


Figure 3.7: General flowchart for the second ABC method.

Algorithm 1 Pseudo-code for the modified HBSFmethod.

```
Set the parameter values and initialize random solutions for each site.
for Fixed number of expeditions (k) do
  Determine number of bees at each forage site, and compute the nectar amount of each
  forage site.
  for All the employed bees and scout bees do
    Determine the profitability of each site considering a noisy assessment.
    if Bee is successful in getting a profitability value larger than the threshold then
      if Is an employed forager then
        Stays that way.
      else if Is a forage explorer then
        Bee becomes an employed forager.
      else
        Bee becomes an observer bee.
      end if
    end if
  end for
  Set probability of becoming explorer bee (P_e(k)).
  for All unemployed foragers do
    if Random Number < P_e(k) then
      Bee becomes an explorer. Set the location for exploring on the next expedition.
    end if
  end for
  for All observer bees do
    Observer bees are recruited in a proportional way to the dance strength.
  end for
end for
```

Similarly to the first method, in this one the position of a food source represents a possible solution of the optimization problem and the nectar amount of a food source corresponds to the quality (fitness) of the associated solution. The profitability assessment and the probability of recruitment is made in the same way described in the first method according to Equations (3.1), (3.2), (3.4) and (3.6). In this way, a neighbourhood search is realized by the recruited observers based on Equation (3.7), which alters one of the positions in the solution vector of the site.

$$v_{ij} = x_{ij} + \phi(x_{ij} - x_{kj}) \tag{3.7}$$

where $k \neq i$ and j are randomly chosen indexes. ϕ_{ij} is a random number between -1 and 1, which controls the production of a neighbour food source position around x_{ij}. Equation (3.7) shows that as the difference between the parameters of the x_{ij} and x_{kj} decreases, the

perturbation on the new position x_{ij} decreases. Thereby, as the search approaches to the optimum solution in the search space, the step length is adaptively reduced [16].
So, the algorithm begins initializing a random population (random solutions to the optimization problem) whose size is equal to the number of employed and onlooker bees. Here, a while loop begins until a stopping criteria is met (number of expeditions). In this loop, first the profitability of each site is assessed and its size is determined (determine how many onlooker bees should be recruited to each site). Then, the onlooker bees are recruited and their fitness is assessed. After this, a dominant bee is chosen for each site, so if a site is not improving it is abandoned and replaced by a site of a scout bee. At the end of each iteration, the colony has two parts to its new population: dominant bees from selected sites, and selected scout bees. Algorithm 2 summarizes, in a pseudo-code, the general aspects of the artificial bee colony algorithm described above.

Algorithm 2 Pseudo-code for the second ABC method.

```
Set the parameter values.
Set an initial random population (Initial sites - One employed bee per site).
for Fixed number of expeditions do
    Compute the nectar amount of each forage site.
    Determine dance strength.
    Determine number of onlooker recruited bees for each site, proportionally to the dance
    strength.
    Set the exploration results of each site by exploiting main solutions.
    Compute the Nectar amount of the exploration results.
    if Profitability of the bee's exploration result is greater than site's profitability then
        Bee becomes the main bee of the site.
    end if
    Select the best bee of each site.
    Compute the Nectar amount of the new best sites.
    if new best site of the main bee does not show a considerable improvement in its
    suitability then
        Bee becomes an explorer.
    end if
    The abandoned site is replaced with the site of an explorer bee more suitable than the
    abandoned one.
    Find and storage the best site of the expedition.
end for
```

3.2.2 Linear Programming Method

The first proposed methodology for the reconfiguration task, 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 equation (3.8), 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.

$$t_{ij} = K_{ij} TMS_i \qquad , \qquad K_{ij} = \frac{0.14}{(I_{fallaj}/xI_{ni})^{0.02} - 1} \tag{3.8}$$

These operating times must comply with the back-up margin given in equation (3.9), 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, as shown in equation (3.10).

$$t_{back-up} - t_{main} \geq 0.3 \qquad \longrightarrow \qquad -t_{back-up} + t_{main} \leq -0.3 \tag{3.9}$$

$$-TMS_i \leq -TMS_{iMinimum} \tag{3.10}$$

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 (3.8), (3.9) and (3.10). Finally, the whole problem can be written as shown in equation (3.11).

$$\begin{aligned} \underset{X}{\text{minimize}} \quad & [f][X] \\ \text{subject to:} \quad & [A][X] \leq [b] \\ & [A_{eq}][X] = [b_{eq}] \end{aligned} \tag{3.11}$$

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 function “linprog” of MatLab, which is the tool used to solve this optimization problem in the algorithm.
Finally, the three methods described above were implemented using the software MatLab. Its validation and debugging was made in a simple radial system devised by myself, which is described in annex C. The parameters given by these three methods were used in the software ETAP to validate the correct coordination of the overcurrent function in the recloser devices, and the results were satisfactory. Table 3.2 shows the values that represent the sum of the parameters (TMS) obtained with each method in the simple radial system coordination task. A lower value of these sum would mean a shorter operation time of the protection system.

Table 3.2: Comparison of results between the three methods

	No. of Expeditions			
Method	**100**	**200**	**500**	**1000**
First Method	0.77	0.76	0.70	0.62
Second Method	0.76	0.74	0.68	0.61
Linear Programming	0.71			

In table 3.2 it is possible to observe that the results of both heuristic methods based on bee behavior are very similar, and that the result of the linear programming method is better than ABC methods for the cases with less than 500 expeditions. Different considerations should be taken when deciding for any of this methods, as all of them are a very useful tool to easily coordinate the operation of overcurrent relays.

Furthermore, a simulation tool was implemented to generally show the behavior of the proposed protection system incorporating the automatic method for reconfiguring overcurrent relays. It a very interactive tool to easily make changes in the topology of the system, observe the general behavior of the multi-agent system and obtain the adjustment parameters for each new condition of operation. More information about this tool can be found in annex A.

Chapter 4

Application in a IEEE Standard Distribution Circuit

The proposed multi-agent system has been tested in a modified version of the IEEE 37 node test feeder. This system is implemented in order to observe some other features of the proposed multi-agent system. The modified version eliminates one node with a transformer, eliminates the voltage regulator, and assumes a balancing load. The size of this circuit allows the test of the zoning procedure and other features of the proposed system. The figure 4.1 shows the mentioned circuit, the necessary information about the system is found in annex C.

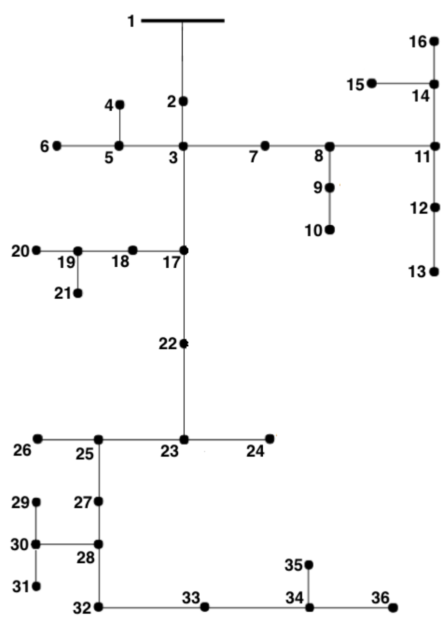


Figure 4.1: Standard Circuit for tests in the second stage.

In this example, is important to show initially the zoning procedure of the system, which is essential for the implementation of the proposed protection system. 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 in order to show the behavior of the system when DG is involved. A 500kW generator in the bus 36, a 400kW generator in the bus 12 and a 150kW generator in the bus 31.

The system is divided into 6 zones as shown in figure 4.2. 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.

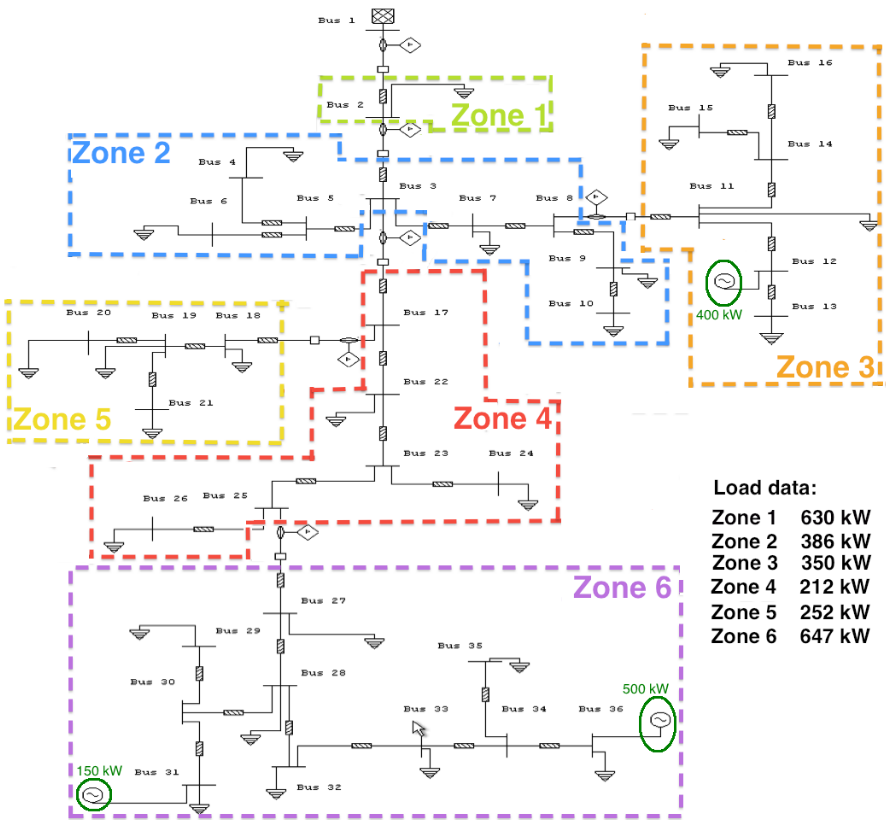
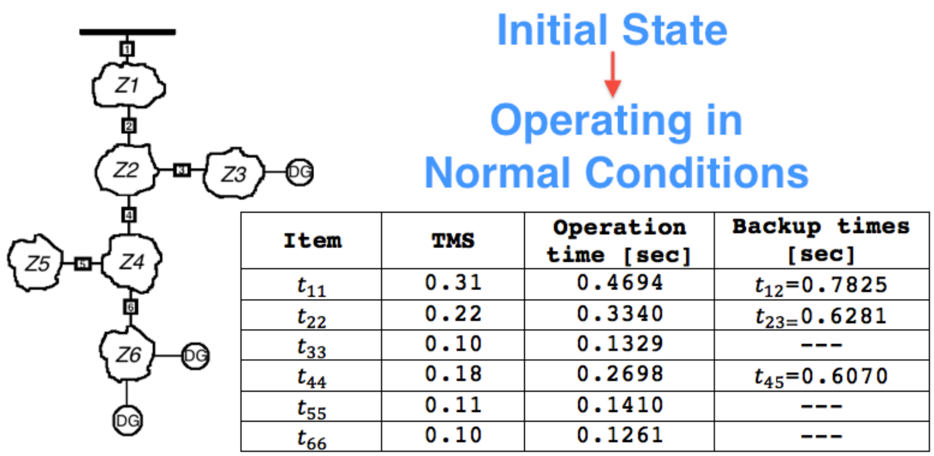


Figure 4.2: Zoning of the system for implementing the proposed protection system.

Example

Now, is presented an example that shows some features of the proposed protection system in the IEEE standard system using the zoning shown in figure 4.2. The sequence of operation obtained in ETAP is not given here due to the image size of the system. Instead, a table with the operating times and TMS values is presented. At each step, a figure is shown to easily see the state of the system.

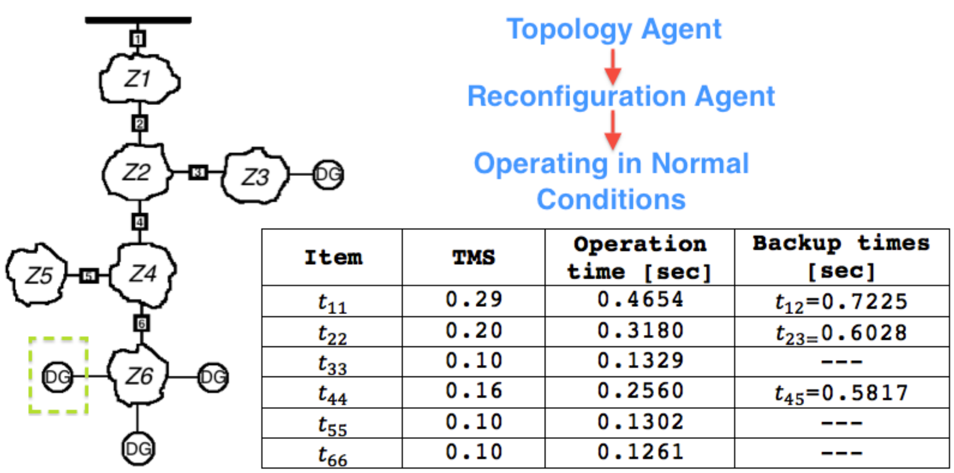
1. The system is loaded in the tool. In figure 4.3 the initial state of the system and the configuration parameters of the protection devices with the corresponding operating times are presented.



Item	TMS	Operation time [sec]	Backup times [sec]
t_{11}	0.31	0.4694	t_{12}=0.7825
t_{22}	0.22	0.3340	t_{23}=0.6281
t_{33}	0.10	0.1329	---
t_{44}	0.18	0.2698	t_{45}=0.6070
t_{55}	0.11	0.1410	---
t_{66}	0.10	0.1261	---

Figure 4.3: Initial State of the modified circuit IEEE standard.

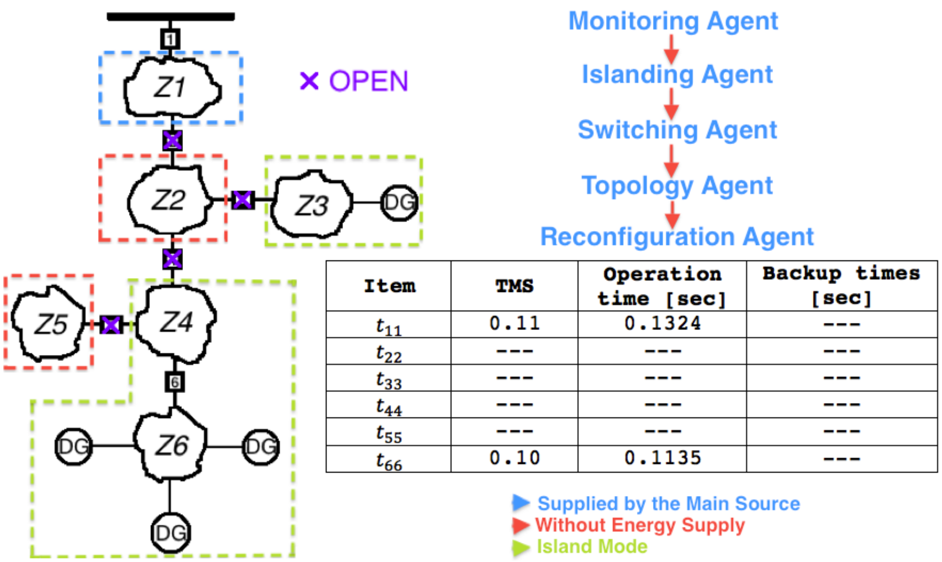
2. A distributed generator of 300kW is included in bus 33 (Zone 6). This generator must be a synchronous machine to ensure the proper supply of the reactive power needed. Besides, its capacity is chosen in order to show the islanding philosophy of the proposed system. With this change, the system remains operating in normal conditions and its protection devices have been adjusted as displayed in figure 4.4.



Item	TMS	Operation time [sec]	Backup times [sec]
t_{11}	0.29	0.4654	t_{12}=0.7225
t_{22}	0.20	0.3180	t_{23}=0.6028
t_{33}	0.10	0.1329	---
t_{44}	0.16	0.2560	t_{45}=0.5817
t_{55}	0.10	0.1302	---
t_{66}	0.10	0.1261	---

Figure 4.4: 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 4.5, the state of the system, after the fault, is displayed. It 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}	0.11	0.1324	---
t_{22}	---	---	---
t_{33}	---	---	---
t_{44}	---	---	---
t_{55}	---	---	---
t_{66}	0.10	0.1135	---

Figure 4.5: 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 4.6. After this restoration process, the protective devices are reconfigured and the system operates again in normal conditions.

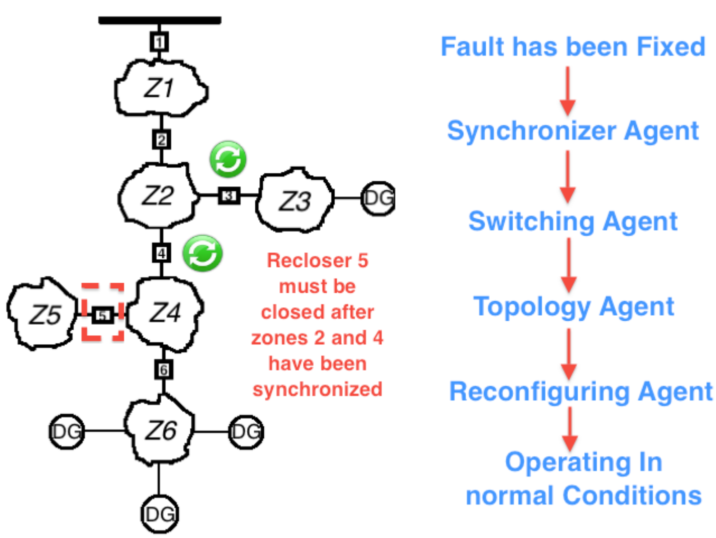


Figure 4.6: Restoration of the IEEE standard circuit.

In this example, some of the features of the proposed protection system were presented. It 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 is a very important issue to increase reliability of the system.

In the presented example can be observed some important desired features of the proposed multi-agent system. Besides, it is clearly highlighted the importance of an automatic reconfiguration of the parameters in the protective devices after a change in the system is detected. The system was implemented in the software ETAP and tested with the obtained parameters, finding that all the devices were properly coordinated and that respond to any fault presented in the system.

Chapter 5

Discussion

The proposed protection system states an alternative to face the challenges in the protection 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. The proposed architecture 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. In this case, 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 or from database. 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, which clearly has a very low probability.

As shown in section II, the heuristic methods based on bee colony behavior obtain better results than the linear programming method for more than 500 expedition, which means a greater execution time of the algorithm with such methods. However, it must be taken into account that with the linear programming method there is a preliminary task of creating the matrices shown in Equation (3.11) based on the current state of the system, which could be a very demanding task. Hence, for circuits where a large number of reclosers are involved, the creation of such matrices will need a big amount of processing resources and could exist some problems with its storing due to their size.

On the other hand, from the two bee behavior based methods is possible to observe some characteristics. Even though, both obtain very similar results, the first method based on [21] ensures a better exploration of the profitable landscape, while the second method based on [16] focus more in the exploitation of some sites. However, the first method holds more firmly the basic principles of the real bee colony behavior.

The proposed architecture for the protection scheme, assumes the use of "smart reclosers" 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 proposed conceptual architecture and the communication system, among others.

Chapter 6

Conclusions

- All the objectives stated were fully met; the conceptual architecture of the protection system 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. The reconfiguration task was solved with three different methods, and an interactive tool was implemented to show and simulate the behavior of the system.

- 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 proposed multi-agent system, 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. Besides, the proposed system entails an adaptive philosophy.

- The three proposed methodologies for the reconfiguration task are correctly coordinating the overcurrent function of the recloser units. Such methods would represent a very interesting option to face the necessity of an adaptive protection philosophy in distribution networks with DG.

- The methodologies proposed in this dissertation are based on a simulation environment, so 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 general behavior of the multi-agent system, 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, Electronic 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

Application in a Simple Radial System

The system 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 3 and its data is given in annex C.

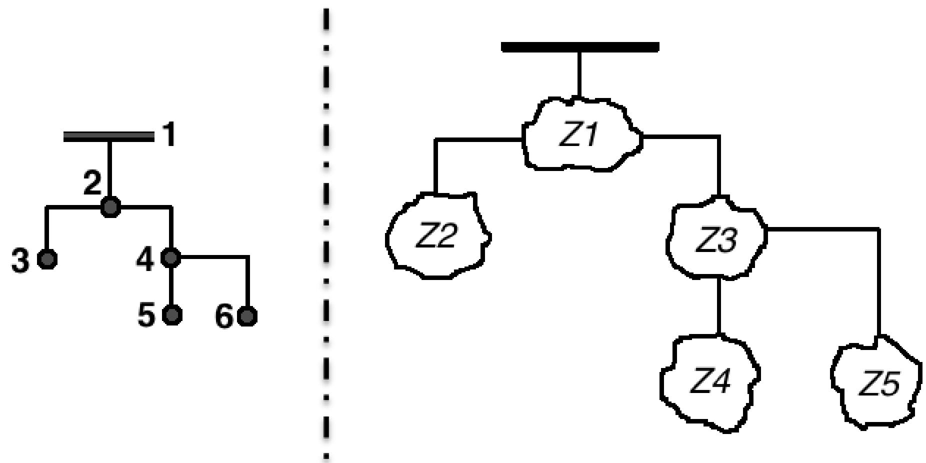


Figure 3: Circuit for tests in the first stage.

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 3. 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, 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.

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

Zone	¿Operating?	¿Island Mode?	Relay	TMS
1	1	0	1	0.26
2	1	0	2	0.11
3	1	0	3	0.21
4	1	0	4	0.11
5	1	0	5	0.11

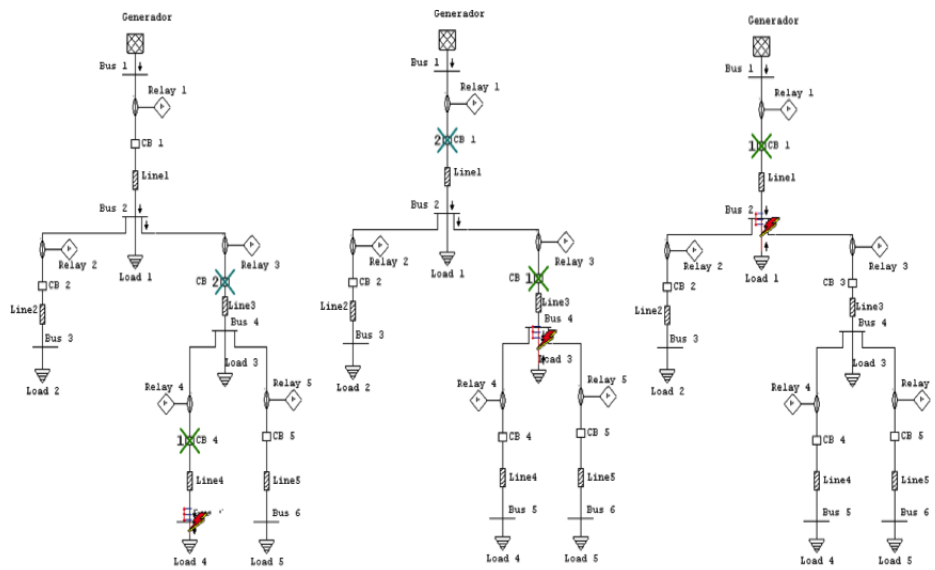


Figure 4: Initial state of the simple radial system.

of the reclosers for such TMS values, are shown in figure 5. All the zones remain operating in normal conditions, but coordination parameters have changed.

Zone	¿Operating?	¿Island Mode?	Relay	TMS
1	1	0	1	0.16
2	1	0	2	0.10
3	1	0	3	0.13
4	1	0	4	0.10
5	1	0	5	0.11

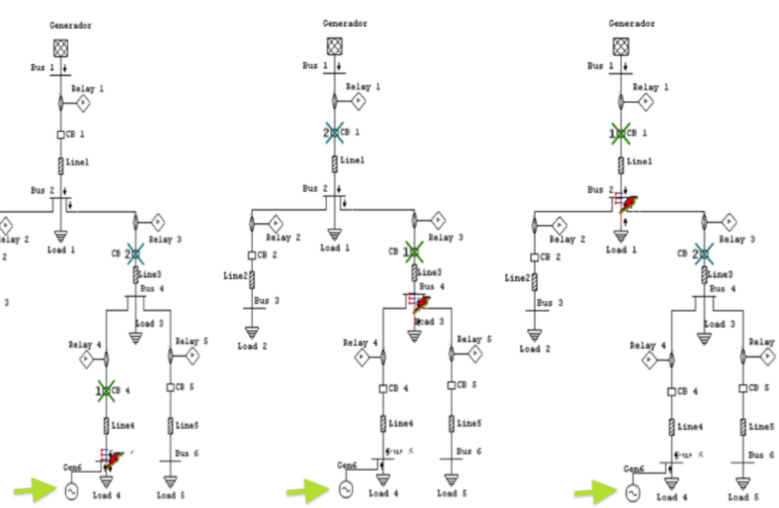


Figure 5: State of the 6 nodes radial system, after including DG in the bus 5.

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 monitoring agent has detected a fault, the switching agent has made its reclosure process and the fault remains.*
    - *Switching agent clears the fault and monitoring agent sends the corresponding information to the topology agent.*
    - *The following zones are without supply of power: 3, 4 and 5.*
    - *Islanding agent assesses the possibility of island modes.*
    - *Zone 4 is able to operate in island mode.*
    - *Island agent sends the corresponding signals to the switching agent to isolate the zone.*
    - *Zone 4 is now supplied by DG inside it.*

    In the figure 6, 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.

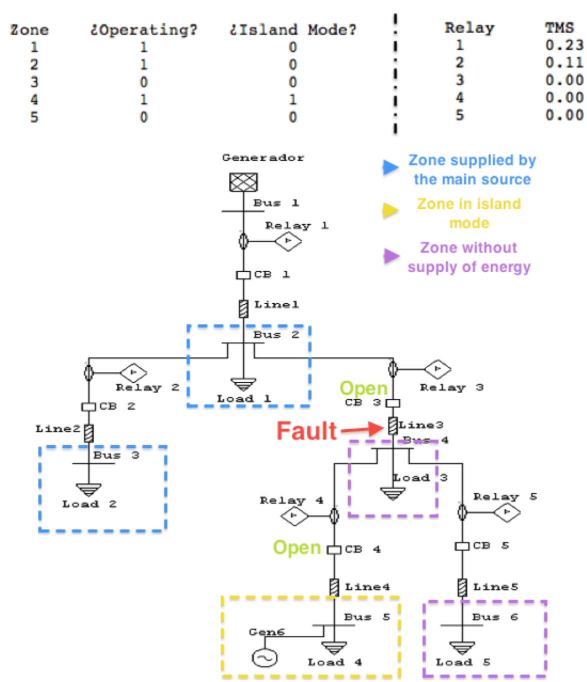


Figure 6: State of the system after a fault occurs in the branch between nodes 2 and 4.

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 7 . If the recloser does not have synchronizer, the DG in the zone has to be disconnected and 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 5. The messages given by the tool are shown below.

- *The supervisory center informs that the fault has been fixed.*
- *Synchronizer agent sends the corresponding signals to the switching agent and the zones are properly synchronized.*
- *In the following zones, the energy supply has been restored: 3, 4 and 5.*
- *The following zones have ceased to operate in island mode: 4.*

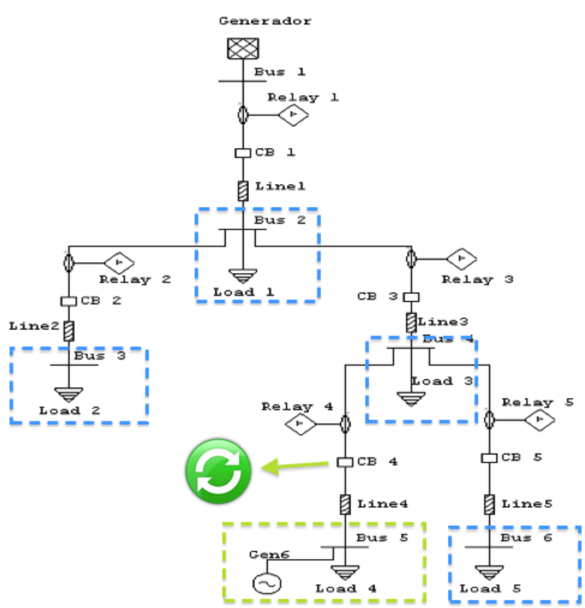


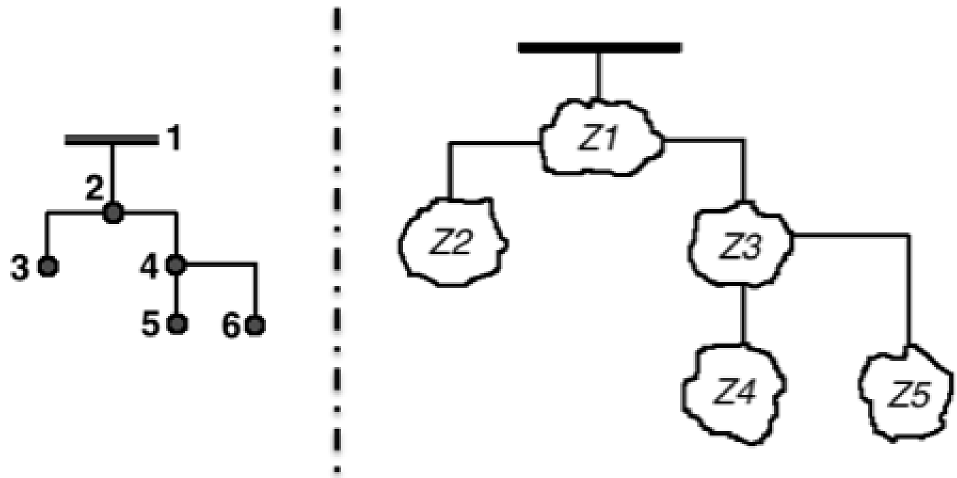
Figure 7: Restoration of the system.

In the previous example, the proposed protection system 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.

Annex C

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 8: Simple Radial System Data.

IEEE 37 Node Test Feeder Data

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 9: IEEE 37 Node Test Feeder Data.

Annex D. Literature Review

“Operation of a Multi-agent System for Microgrid Control”	Journal	**1**
Key words: **Auction algorithm**, distributed generation, energy market, microgrids, multi agent system, and symmetrical assignment problem.	2005 IEEE TRANSACTIONS	

What is done?	Assessment
• Presents the operation of a multi-agent system (MAS) for the control of a microgrid. • Uses a classical distributed algorithm based on the symmetrical assignment problem for the optimal energy exchange between the production units of the Microgrid and the local loads.	• It proposes a hierarchical structure with a central device, which seems to go against the basic characteristics of the DAI concept in multi-agent systems. • It focuses only in the market operation and leaves aside other aspects of microgrid control like protection and monitoring.

“Implementation of a new protection scheme on a real distribution system in presence of DG”	Conference	**2**
Key words: Distribution Generation, Distributed System, Protection and **Load Shedding**.	2009 Tehran, Iran	

What is done?	Assessment
• A new protection scheme for distribution systems in presence of DGs is proposed. • A load-shedding algorithm based on load importance. • The proposed scheme is implemented on some part of a real distribution network in Shiraz, which is a large city in Iran.	• Is not clear which technique is used for the optimization problems stated. • The devices needed for the proposed scheme are not specified, it seems be based in several assumptions. • It doesn't have an adaptive philosophy, which is essential in a distribution system with DG.

“Applying Multi-Agent System Technology in Practice: Automated Management and Analysis of SCADA and Digital Fault Recorder Data”	Journal	**3**
Key words: **Cooperative systems**, decision support systems, fault diagnosis, intelligent systems, knowledge-based systems, power transmission protection.	2006 IEEE TRANSACTIONS	

What is done?	Assessment
• Use of multi-agent system technology to automate the management and analysis of SCADA and digital fault recorder (DFR) data. System called PEDA. • Is demonstrated that PEDA supports protection engineers by providing access to interpreted power systems data via the corporate intranet within minutes of the data being received. • The use of existing agent development toolsets and standards is also discussed.	• It shows an interesting way to incorporate multi-agent systems in actual power systems, having in mind the actual technology. • It makes a very good summary of the existing toolsets and standards on development of agent systems. • Perhaps because of their attempt to use the actual SCADA system, the multi-agent architecture proposed doesn’t seem to be totally decentralized.

“Dispatch of distributed generators using a local replicator equation”	Conference	**4**
Key words: Distributed control, economic dispatch, evolutionary game theory, **replicator dynamics**, and resource allocation.	2011 Orlando, FL, USA	

What is done?	Assessment
• Proposition of a novel agent-coordination method that they refer to as the local replicator equation, using the basic properties of replicator dynamics. • An economic dispatch in distributed generation systems is presented in order to illustrate the theoretical results.	• It shows an interesting idea of incorporating the philosophy of multi-agent system with a replicator dynamics model in order to reach a common fitness. • It shows that the stability of the equilibrium points and the simplicity of the model allow this technique to be applied in a general distributed environment.

“Optimal Overcurrent Relay Coordination in Distribution System”	Conference	**5**
Key words: Distribution system, **genetic algorithm**, graph theory, meshed, overcurrent relays.	2012 Delhi, India	

What is done?	Assessment
• Assessment of applying artificial intelligence	• It states the optimization problem in the

• for optimal coordination of overcurrent relays. • Discussion of the application of genetic algorithm for optimal coordination of overcurrent relays, considering the combination of primary and backup relays.	coordination of overcurrent relays but doesn't have in mind the problem of misoperation between primary and backup relays.

Optimum Coordination of Overcurrent Relay Timing Using Continuous Genetic algorithm	Journal	**6**
Key words: Constrained optimization, **Continuous genetic algorithms**, Linear programming problem and **Overcurrent relay coordination**.	2011 ELSEVIER	

What is done?	**Assessment**
• Its purpose is to find an optimum relay setting to minimize the time of operation of relays and at the same time, to avoid the mal-operation of relays. For this, they use a continuous genetic algorithm technique (CGA).	• It proposes a very curious optimization problem for relay coordination, incorporating the constraints in the fitness function in order to make use of penalty method and avoid mal-operation of primary and backup relays.

"Optimal coordination of overcurrent relays using Honey Bee Algorithm"	Conference	**7**
Key words: Power system protection, Optimal coordination, Relay settings, Overcurrent relays and **Honey bee algorithm**.	2010 Zanjan, Iran	

What is done?	**Assessment**
• Selecting the relay settings is to achieve the minimum possible operating times while maintaining coordination among all relays. • Relay coordination problem is solved using the Honey Bee algorithm, which is one of the heuristic techniques capable of solving constrained optimization problems.	• The proposed honey bee algorithm is based on a modified neighborhood search but maintains the basic characteristics of this kind of algorithms. • The results obtained are mentioned to be better in comparison to other works, which apply intelligent algorithms.

"Optimal Overcurrent Relay Coordination Using Artificial Bees Colony Algorithm"	Conference	**8**
Key words: Relays, Optimal coordination, Artificial intelligence, **Bees colony algorithm**, Particle swarm optimization, Newton method.	2011 Nakhon, Thailand	

What is done?	**Assessment**
• Presents optimal coordination of overcurrent relays by using artificial bees colony algorithm. • The control variables used in this paper are the pickup current and time dial setting of relays. • Quasi-Newton (BFGS), particle swarm optimization (PSO) and artificial bees colony (ABC) are employed to evaluate the search performance.	• Makes a very good comparison the three methods for solving the optimal OCR relays coordination problem. • The results show that the artificial bees colony algorithm (ABC) is capable to minimize the operation time of relays in the entire system, obtaining a lower value of TMS_{TOTAL} than BFGS and PSO.

"Decision Making Model in Multi-agent System"	Conference	**9**
Key words: Multi-agent system, **decision-making**, decision making mechanism, learning wheel.	2011 Beijing, China	

What is done?	**Assessment**
• It analyzes multi-agent system and dynamic decision-making mechanism, and presented learning wheel in decision-making.	• It tries to analyze the decision-making process based on human mental activity but doesn't present a clear analogy for multi-agent systems.

"Honey bee social foraging algorithms for resource allocation: Theory and application"	Journal	**10**
Key words: Ideal free distribution, **Honey bee social foraging**, Evolutionarily stable strategy, Dynamic resource allocation, Temperature control.	2010 ELSEVIER	

What is done?	**Assessment**
• A model of honey bee social foraging is introduced to create an algorithm that solves a class of dynamic resource allocation problem. • Is proved that if several such algorithms compete in the same problem domain, the strategy they use is a Nash equilibrium and an evolutionarily stable strategy.	• It shows in a very comprehensible way the analogy of honey behavior in the dynamic resource allocation problem, even though it doesn't try to mimic the whole behavior of the foraging process, it tries to focus in the recruitment process by the waggle dance. • The results obtained in the temperature

• The proposed method is tested solving a dynamic voltage allocation problem to achieve a maximum uniformly elevated temperature in an interconnected grid of temperature zones.	control problem using the HBSFA demonstrate the functionality of such methods in dynamic resource allocation problems.

"A modified Artificial Bee Colony algorithm for real-parameter optimization"		Journal	**11**
Key words:	Swarm intelligence, Self-organization, Artificial Bee Colony algorithm, Real-parameter optimization.	2010 ELSEVIER	

What is done?	**Assessment**
• It proposes a modified version of the Artificial Bee Colony algo- rithm and is applied for efficiently solving real-parameter optimization problems.	• Even though the algorithm is modified to solve real-parameter optimization, the analogy of honey behavior with the proposed algorithm is clear and maintains the bases.

"An Autonomous Agent-based Framework for Self-Healing Power Grid"		Conference	**12**
Key words:	Power grid, Autonomous web service, Hierarchal **self-healing framework** and Failure detection.	2009 Texas, USA	

What is done?	**Assessment**
• It proposes a self-healing framework that employs advanced failure diagnosis techniques along with autonomous web services to provide temporary recovery solutions. • It also provides a cognitive planning cycle to find ultimate corrective solutions as well as evaluation service to verify the effectiveness and performance of the final solution.	• The proposed scheme seems to meet all the requirements of multi-agent systems. The design is based in layer architecture and contains different kind of agents both reactive and deliberative. • In the dissertation is not clearly specified the role and tasks of each agent mentioned.

"Multi-Agent Systems in a Distributed Smart Grid: Design and Implementation"		Conference	**13**
Key words:	Distributed smart grid, **multi-agent system** and microgrid.	2009 Arlington, USA	

What is done?	**Assessment**
• Discuss the design and implementation of a multi-agent system that provides intelligence to a distributed smart grid at a distribution network. • The simulation results indicate that the proposed multi-agent system can facilitate the seamless transition from grid connected to an island mode when upstream outages are detected.	• The architecture proposed is well founded and seem to act in a decentralized way with four kinds of agents; a control agent, a DER agent, an user agent and a database agent. • It gives a very good approach to the process that must be followed to apply or realize the architecture in the current network. • It bases on the standard on Foundation for Intelligent Physical Agent (FIPA).

"Multi-Agent Application of Substation Protection Coordination with Distributed Generators"		Conference	**14**
Key words:	Substation, **Protection Coordination**, Distributed Generation and **Multi-agent technology**.	2005 Hong Kong, China	

What is done?	**Assessment**
• A coordination multi-agent system is proposed with the functions of the agents described. • Relay coordination strategy is also discussed and communication simulation is carried out on the Java agent Development Framework (JADE) platform.	• An interesting summary of DG impact on substation protection and coordination is developed. • It doesn't focus on the agent's roles and tasks but in communication of this agents and message structure.

"Implementing Cooperative Agent-based Protection and Outage Management System for Power Distribution Network Control"		Conference	**15**
Key words:	Distributed Artificial Intelligence (DAI), **Multi-Agent Systems (MAS)**, **cooperative systems**, power distribution network, protection and restoration.	2010 Selangor, Malaysia	

What is done?	**Assessment**
• The proposed MAS is implemented using (JADE), which is fully accomplished in Java and compliant with (FIPA). • In order to power restoration decisions, Binary	• The proposed MAS technology seems to offer a modular, extensible, adaptable and versatile approach. • A very interesting approach to system

Knapsack Problem (KP) optimization algorithm is implemented with PROLOG. • It is shown that, MAS technology's impact on outage management makes it be autonomously performing and effective cooperative.	restoration issues using binary Knapsack optimization is given. • The system is implemented on a real distribution network, which gives very good conclusions of the system.

"Implementing Multiagent Systems Technology for Power Distribution Network Control and Protection Management"		Journal	**16**
Key words:	Artificial intelligence, **cooperative systems**, power distribution protection, underground power distribution lines.	2006 IEEE TRANSACTIONS	
What is done? • An extended research in possible high-end protection and control methods is presented. • A flexible and versatile multia-agent system (MAS) is proposed. • The authors intend to show the efficiency of combining modern IT techniques with the equipment provided by distribution automation evolving technology.		**Assessment** • It gives a very complete description of the message protocol between the devices, but it does not present a clear architecture of the MAS. • It gives a good approach to distributed control of electrical protections, considering that the system must maintain stability even if the actions of agent communities are not synchronized.	

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TITULO DEL TRABAJO DE GRADO:

An Adaptive Multi-Agent Approach to Protection Systems in Distribution Circuits with Distributed Generation

DESCRIPCIÓN FÍSICA

Número de páginas: 54

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*RESUMEN DEL TRABAJO DE GRADO:

This graduation project proposes an adaptive multi-agent protection system for distribution networks when distributed generation is incorporated. Initially, the main issues in electrical protections when DG is included and the importance of an adaptive philosophy are discussed. A conceptual architecture of the system with the expected features of the protection scheme is proposed, taking into account the process of detecting faults, isolate faulty zones, detect and create possible island modes, and finally restore the total operation of the system. Additionally, three methods for the automatic reconfiguration of overcurrent relays are proposed; two of them based on an artificial bee colony algorithm and the last one based on a linear programming method. Some of the features of the proposed protection scheme are tested in the IEEE 37 node test feeder.

OBJETIVOS DEL TRABAJO DE GRADO:

METODOLOGÍA DEL TRABAJO DE GRADO:

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Multi-Agent Systems, Artificial Bee Colony, Distributed Generation, Adaptive Electrical Protections.

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