A Decentralized Negotiation Framework for Restoring Electrical Energy Delivery Networks with Intelligent Power Routers - IPRs

By

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ABSTRACT

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Current Electrical Energy Delivery Networks (EEDN) are managed from a centralized operations and control center. In the event of a system failure, human operators at this control centers device schemes for restoring the system back into an operational state. Such a scheme is inefficient and unreliable since a crippling failure at the control center would render the system useless. In this thesis, we present a decentralized framework to help control and manage an Electrical Energy Delivery Networks (EEDN). Our scheme is based on the idea of modelling the EEDN as a data network. The paths taking the flows of power are then controlled by devices that we call Intelligent Power Routers (IPRs). These IPRs monitor the status of the network, and when a failure occurs, they work together to open new paths to send power from the generators to the consumers (e.g cities, factories, hospitals). In this thesis, we present the architecture of our solution, and show distributed algorithms for a particular problem: restoring the undamaged part of a EEDN after a major failure. Our experiments demonstrate that our approach is reliable, effective, and scalable. More importantly, our approach can find restoration solutions that are efficient, and sometimes as good as those produced by centralized algorithms. We present a first prototype of IPRs network that has a satisfactory performance for system restoration using the new approach.

RESUMEN

Un Esquema Descentralizado para Restaurar Redes de Potencia Eléctrica utilizando Enrutadores Inteligentes de Potencia

Por

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Actualmente las redes de transmisión y distribución de potencia eléctrica son administradas desde un centro de control. Cuando ocurre una falla en el sistema, los operadores en este centro de control utilizan esquemas de restauración para llevar al sistema nuevamente a un estado operacional. Este esquema tiene la debilidad que sí el centro de control es afectado por la falla, el sistema no puede ser restaurado. El esquema propuesto en esta tesis se basa en la idea de modelar las redes de Potencia elétrica como una red de transmisión de datos. Los caminos utilizados para transmitir potencia eléctrica son controlados por unos dispositivos llamados Enrutadores Inteligentes de Potencia. Estos dispositivos monitorean el estado del sistema, y cuando ocurre una falla, ellos trabajan juntos para establecer nuevos caminos para transmitir potencia desde los generadores hasta los consumidores (Ciudades, fábricas, Hospitales). En esta tesis presentamos la arquitectura propuesta para nuestra solución y los algoritmos distribuidos para un problema particular: restaurar la mayor parte posible del sistema de potencia luego de un disturbio mayor. Nuestros experimentos muestran que nuestra propuesta es confiable, efectiva y escalable. Lo más importante es que nuestra propuesta logra encontrar esquemas de restauración efectivos y en algunas ocaciones tan buenos como los centralizados. Presentamos el primer prototipo de Enrutadores Inteligentes de Potencia, el cual tuvo un buen desempeõ para la restauració de diversos sistemas de potencia.

To my family, wife Carmen, father Idálides, mother Rosalba and sister Neifa

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CHAPTER 1

Introduction

1.1 Overview

Every social and economic function of our society depends on the secure and reliable operation of the electric power network [1]. Existing Power Delivery Systems are designed with redundant power generators and delivery lines to make the system tolerant to failures on these elements [2]. However, the control and coordination of the process to generate, transmit, and distribute power still occurs in a centralized manner, with only a few sites (control centers) managing mission-critical tasks for power generation and delivery [3]. This centralized scheme has a clear drawback: a failure in one of these control centers might result in the total collapse of the system. Therefore, it is highly desirable that future Electrical Energy Distribution Networks (EEDN) have the capabilities for automating and distributing the tasks of coordinating and controlling the power generation, transmission, and distribution components when contingencies or emergency situations occur [1]. Our idea is to have enough intelligence and redundancy throughout the system to survive failures, and then quickly recover from them.

1.2 Problem Statement

Our society is highly dependant on EEDN therefore its high reliability is always required. Whenever a group of consumers are de-energized by a failure in the EEDN, it is necessary to restore the electrical service as soon as possible to enable the consumers to continue with their activities. Currently, EEDN are controlled from a centralized control center that receives measurement from power generator and transmission lines. When an electric power supply interruption is caused by a fault in any system component; engineers and operators at the command center start working to promptly restore the power system to an optimal target configuration through a Power Restoration Process [2]. Thus, Power Restoration is the process performed by the control center after a fault or blackout occurrence in which the system elements are reconfigured and re-energized with the objective of restoring the service to as many de-energized consumers (called "loads") as possible. To obtain the target configuration in a restoration process, various approaches have previously been proposed, which can be roughly classified into four categories: heuristics, expert systems (ESs), mathematical programming (MP), and soft computing [2]. But, all these restoration methods are centralized processes that are launched and coordinated from the control center.

The question that must be raised here is: what would happen if the control center is also affected by the fault? In addition, the restoration process could be a slow and error prone process due to factors such as: a) overwhelming amount of data, b) miss-communications on the part of operators, c) lack of coordination between electric utilities sharing the power grid, or d) lack of accurate measurements. The critical issue,as shown in figure 1.1, is that a slow response during a contingency could generate a cascade effect affecting more portions of the system, and even a total system collapse [1].

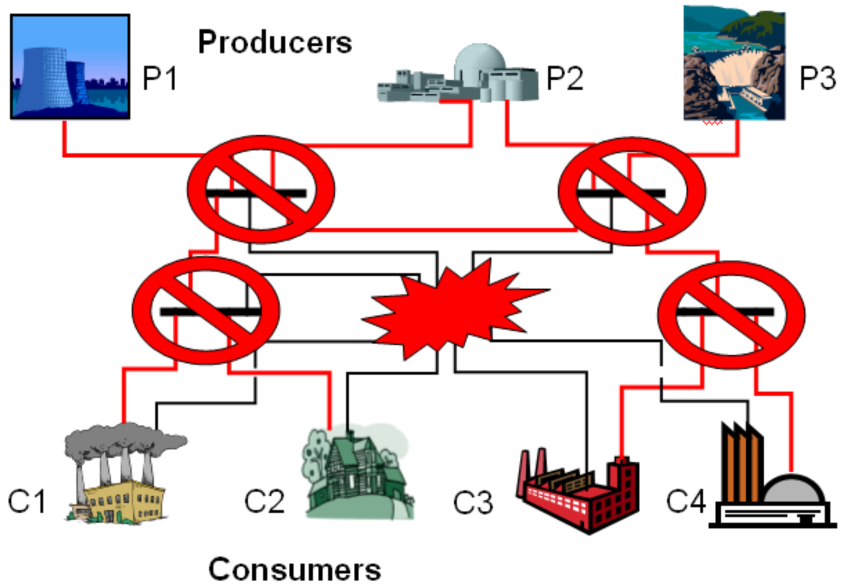


Figure 1.1: A Slow response could cause a cascade failures

1.3 Proposed Solution

At the University of Puerto Rico - Mayaguez, in the Electric Power Networks Efficiency and Security (EPNES) project (sponsored by National Science Foundation (NSF)), we are currently developing technologies for a next generation of EEDN based on a distributed, de-centralized framework for control and communication between system components. In our framework, the intelligence that can be used for control and coordination operations is embedded into a series of computing devices called the Intelligent Power Routers (IPRs)[1]. These IPRs are strategically connected to power generators and power lines, thus enabling them not only to observe current network conditions, but also cooperate with each to active alternate lines to move power from producers to consumers [1]. For example, when power is lost on a given region due to a generator failure, several IPRs in charge of that region might ask another generator to increase power supply and then coordinate to open alternate lines to bring energy into the affected region. Our goal is to show that by distributing network intelligence and control functions using the IPR, we will be capable of achieving improved survivability, security, reliability, and re-configurability as it occurs in Data Networks [4]. This approach borrows from computer networks: a flow of data needed to be established between two geographically distant end-points is implemented via data routers and forwarding protocols. These data routers cooperate by moving pieces of data over the network until the data reaches the desired destination(s). The IPRs in an EEDN could operate in similar fashion with due consideration of the physical differences between data exchange and energy exchange [1].

The IPRs Network will be built with a Peer-to-Peer (P2P) or a mesh architecture in which, for a given IPR, it should be irrelevant whether its inputs come from power producers or other IPRs [1]. In the event of a component or system failure, the IPRs will make local decisions and coordinate a restoration process with other routers to bring the system back to operation, as shown in figure 1.2.

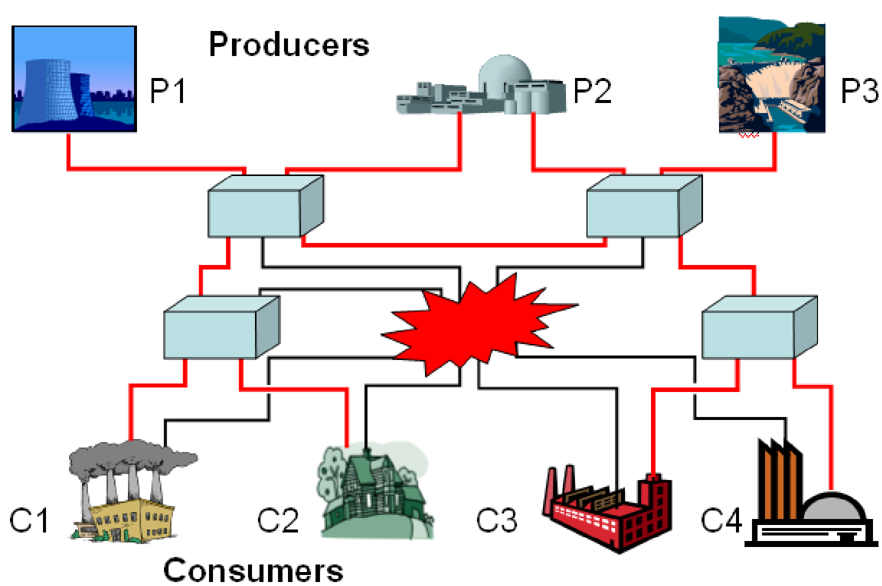


Figure 1.2: IPRS Respond Promptly to Avoid Further Deterioration

But, the proposed scheme will not substitute current control protocols if there are no contingencies. However, under normal operating conditions, the IPRs would provide additional information on system status to the central energy management system. The IPR will allow the system to operate in degraded operation during major contingencies [1].

In the approach previously outlined is obvious the necessity of a robust protocol for distributed control to coordinate all tasks of IPRs network. Figure 1.3 shows the organization of the EPNES project in the UPRM. This thesis is involved in the sections of the IPR Protocols and Restoration Models. In this dissertation, we present aspects associated with the design of this distributed protocol for IPRs and several algorithms to perform restoration process in a distributed way.

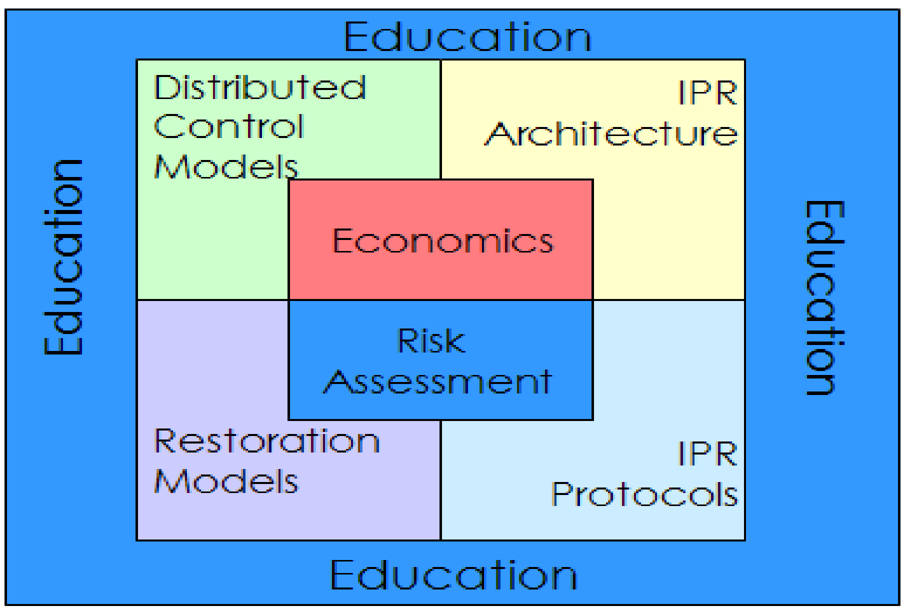


Figure 1.3: Organization of EPNES project at UPRM

1.4 Objectives of this Thesis

The main objective this thesis is to design the communication protocols and negotiation scheme to Intelligent Power Routers to achieve Power System Restoration.

- To design the IPRs Network Architecture
- To design a reliable Control protocols for IPRs network, defining messages types, communication schemes and routing algorithms.
- To design the necessary Algorithms for negotiation during system restoration.
- To develop a functional prototype with capabilities to negotiate power request between IPRs in a network.

1.5 Contributions

The major contributions of this thesis can be summarized as follows:

1. We have established a mapping between Electrical Energy Distribution Networks (EEND) and Wide Area Network (WAN).
2. Design of the architecture and communication protocols and negotiation scheme for distributed negotiation for power system restoration using IPRs, this will complement but not substitute existing control mechanisms.
3. Demonstration of the feasibility of IPRS through several experiments, the obtained results show successful restoration plan for major contingency.

1.6 Thesis Structure

The remainder of this thesis is structured as follows. Chapter two presents a survey of related work arranged in four subtopics: i) Power and delivery systems; ii) Computing networks and routing protocols; iii)Distributed systems and iv) Peer-to-peer architecture. Chapter three presents the basic concepts associated with the of IPR network discussing i) Mapping of Electrical Energy Delivery Networks (EEDN) as a Wide Area Network-WAN; ii) mathematical formulation of an objective function with its associated constraints; and iii)

IPR Network architecture.[1] Chapter four presents the IPRs Network multi-stage negotiation scheme and its components describing i) Design for IPR architecture and distributed control protocol; ii) island-zone approach iii) Message types and iv) Algorithms associated with IPRs. Chapter five presents the experiments and the results obtained. Finally, Chapter six presents the final conclusions and future work.

[1] A network architecture can be defined as the organization of the network, specifying the roles of each element and their relations.

CHAPTER 2

Related Work

2.1 Overview

In this chapter, we present here relevant work upon which this thesis is based. The areas are a) Distributed Systems, b) Computing Networks and Routing Protocols, c) Peer-to-Peer Networks, d) Multi-agent technologies and e) Electrical Power System.

2.2 Distributed Systems

A distributed system is a collection of independent computers that appears to its users as a single coherent system [5]. The main goal of a distributed system is to make it easy for users to access remote resources, and to share them with others users in a controlled way. Likewise, another important goal of a distributed system is transparency, a distributed system that is able to present itself to users and applications as if it were only a single computer system is said to be transparent.

Distributed systems should also be relatively easy to expand or scale as a consequence of having independent computers. But, when a system needs to scale very different types of problems need to be solved such as problems with performance and communications. One of these problem is caused by an enormous number of message that have to be routed over many lines. To combat this problem there exists a technique called Distribution. Distribution involves taking a component, splitting it into a smaller parts, and subsequently spreading those parts across the systems. Domain Name System (DNS) is a good example of distribution in the Internet. The DNS name space is hierarchically organized into a tree of domains, which are divided into non-overlapping zone [5].

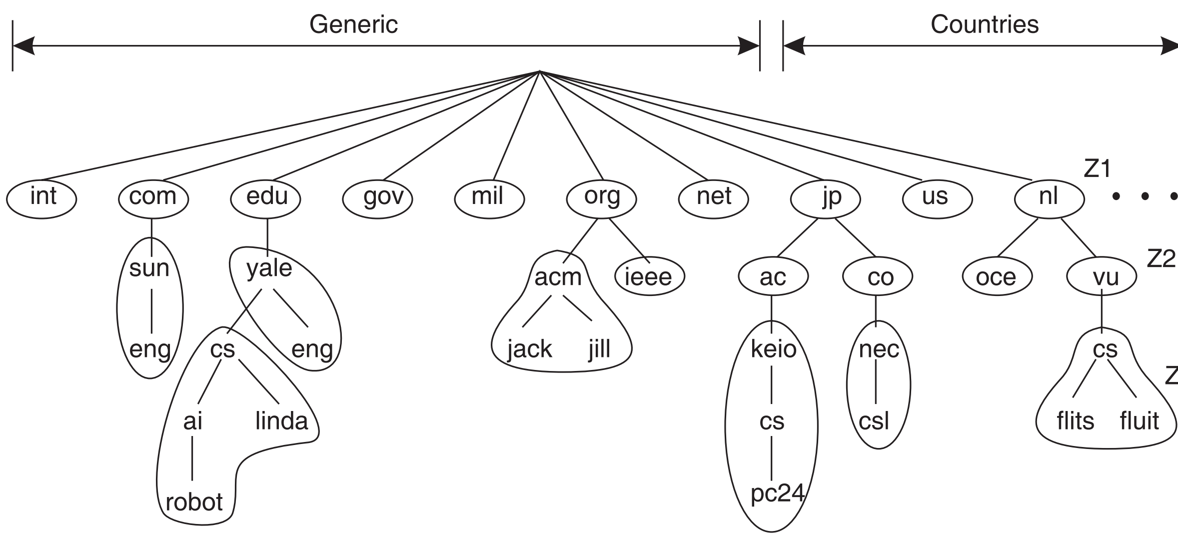


Figure 2.1: The DNS name space is hierarchically organized into a tree of domains

Currently, the development of new Distributed System is strongly supported by the academic, scientific and industrial community. An example of these developments is the Grid Computing innitiative. The early efforts in Grid computing started as projects to link US supercomputing sites, but now, there are many applications that can benefit from the Grid infrastructure, including collaborative engineering, data exploration, high-throughput computing, and of course distributed supercomputing [6].

Another example of Distributed System is the Middleware system. Essentially, middleware is a distributed software layer, or platform which abstracts over the complexity and heterogeneity of the underlying distributed environment with its multitude of network technologies, machine architectures, operating systems and programming languages[6]. Three programming models are the most used in middleware developments. The first is the object based middleware, in which applications are structured into objects that interact via location transparent method invocation(e.g. OMG's CORBA and Microsoft's Distributed COM). The second model is Event Based Middleware, which is particularly suited to the construction of non-centralized distributed applications that must monitor and react to changes in their environment(e.g. process control, Internet news channels and stock tracking). It is claimed that event based middleware has potentially better scaling properties for such applications than object based middleware [6]. Finally, the third model is Message oriented middleware and it is biased toward applications in which messages need to be persistently stored and queued (e.g. Workflow and messaging applications).

2.3 Computer Networks and Routing Protocols

The main function of the network layer of the protocol stack TCP/IP is routing packets from source to destination machines. The routing algorithm is that part of the network layer software responsible for deciding which output line should be used to transmit an incoming packet. Routing is, in essence, a problem of graph theory [4]. Figure 2.2 shows a network represented as a graph. The nodes of the graph may be hosts, switches, routers or networks. The edges represent network links with an associated cost, which gives some indication or cost of the desirability of sending traffic over that link.

The basic problem of routing is to find the lowest-cost path between any two nodes,

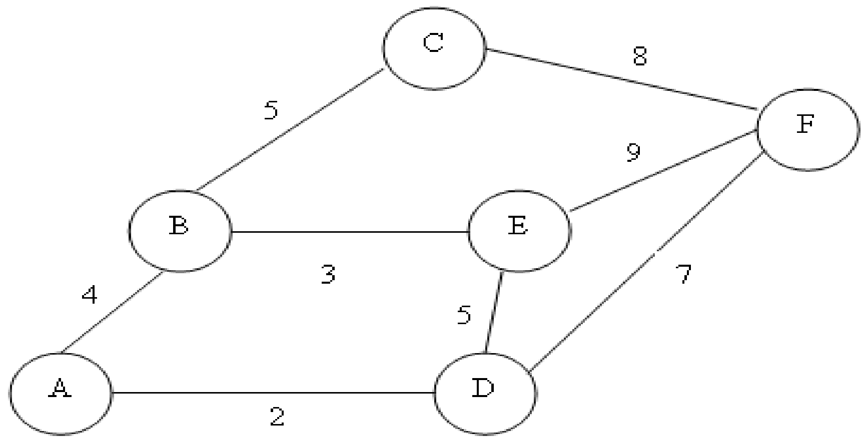


Figure 2.2: Network represented as a graph

where the cost of a path equals the sum of the cost of all edges that make up the path [4].

Routing algorithms can be grouped into two classes: Non-adaptive algorithms and adaptive algorithms. The first are static and they do not make decisions based on current traffic conditions and topology of the network; Adaptive algorithms, on the other hand, change their routing decision to reflect changes in the network. Distance Vector Routing (RIP) and Link State Routing Algorithm belong to the second group and they build routing tables based on shortest path approach.

In the Distance Vector algorithm each node constructs a one-dimensional array containing the "distances" (costs) to all other nodes and distributes that vector to its immediate neighbors. The basic idea behind the Link State Routing protocol is: Every node knows how to reach its directly connected neighbors, and if we make sure that the totality of this knowledge is disseminated to every node, then every node will have enough knowledge of the network to build a complete map of the network. Reliable flooding is the mechanism used to achieve this idea. In this approach each node sends its link-state information out on all of its directly connected links, with each node that receives this information forwarding it out on all of it links, except the source link. This process continues until the information has reached all nodes in the network [4].

A Wide Area Network (WAN), such as the Internet, is organized as interconnected Autonomous Systems (AS), each of which is under control of a single administrative entity and can use its own routing algorithm inside. An Interior Gateway Protocol (IGP) is a routing algorithm used inside an AS, while a Exterior Gateway Protocol is an routing algorithms used by an AS to communicate with another AS.

All an interior gateway protocol has to do is move packets as efficiently as possible from the source to the destination. It does not have to worry about policies of use of an AS[7]. One of Interior Gateway Protocol (IGP) most widely used is Open Shortest Path First Protocol (OSPF) that is a link-state routing protocol design as successor of the original IGP used in the Internet.

Exterior gateway protocol routers have to worry about usage policies a great deal. The Border Gateway Protocol (BGP) has been designed to allow many kinds of routing policies to be enforced in the inter-AS traffic, such as preventing traffic through certain AS (e.g., traffic starting or ending at IBM should not transit Microsoft).

Every routing protocol have been designed to reduce congestion and improve network performance. However, with the growth of multimedia networking, often these protocols are not enough. The Resource reSerVation Protocol (RSVP) is a proposal for a protocol design to reserve resources across a computer network to guarantee quality of service such as portions of bandwidth across communication network. This protocol is oriented to multimedia applications like video transmission. RSVP is receiver-oriented: the receivers of the data flow are responsible of initiating the resource reservation and maintaining the reservation through time using by means of confirmation messages.

2.4 Peer-to-Peer Networks

The client/server model describes the relation between two computer processes programs where one of them (the client) sends a service request to other(the server). This server responds to the client request, but only the client can make a request to the server, no otherwise. The client/server model is based on a distributed model for storage, processing and access to data. Generally, servers are powerful computers or processes dedicated to managing disk drives (file servers), printers (print servers), or network traffic (network servers). Clients are workstations on which users run applications. Clients rely on servers for resources, such as files, devices, and even processing power.

Another type of network architecture is known as a Peer-to-Peer (P2P) architecture because each node has equivalent capabilities and responsibilities, in other words, a peer-to-peer network is a network that does not have a central computer(s) or dedicated server(s). Every element is both a client and a server. In a peer-to-peer network every computer acts on its own and is not dependent on another computer or server, and it allows individual computers to communicate directly with each other and to share information and resources without using specialized servers [8].

This P2P architecture in the past had been applied primarily in smaller networks of less than a dozen computers. However, recently we have seen an explosive growth in the use of file-sharing software in order to exchange digital audio, video and other types of files. The trend was started by Napster, which allows sharing of MP3 music files among an arbitrary set of users. There exist numerous variants of file sharing software including Wrapster (a slight generalization of Napster) and Morpheus (which provides general file sharing with optimized download algorithms using multiple copies based on the Fast-Track protocol). Concurrently, distributed versions of file-sharing have also been developed, including Gnutella and Freenet [9].

Finally, the use of P2P architectures opens up new dimensions of handling and managing the information facilitating the exchange of the most recently created and highly distributed information. The decentralized P2P system provides the potential to be robust to faults or intentional attacks, making them ideal for long-term storage [10].

2.5 Multi-agents Technologies

An autonomous system is a system, which can react intelligently and flexibly on changing operating conditions and demands from the surrounding processes [11]. An agent acts autonomously on the base of information from the environment or other agents. If some information is missing the agent substitutes autonomously its original action scheme by a new one without this information [11]. Beyond this behavior of single agents, teams of agents shall be enabled to achieve a common goal [11].

Two basic configurations of agents are a group of agents with different subtasks and groups of agents of the same kind and the same hierarchical level. The first configuration is covered by the autonomous system definition in which autonomous components as agents request and provide information to other agents. The second configuration needs particular methods like negotiation to reach global goals while keeping local constrains [11].

Multi-agent coordination and cooperation is a basic issue of multi-agent system (MAS). Besides the research and implemention of cooperative agent teamwork, communication among agents also plays an important role [12]. Communication protocols enable agents to exchange and understand message. Interaction protocols enable conversation through structured exchanges of messages [11]. Coordination methods serve to establish conversation between agents. Coordination is based on communication and individual decision-making.

Cooperation is coordination among non-antagonistic agents, while negotiation is coordination among competitive or self-interested agents. The last mechanism does not require a central decision maker or managing instance. The agents have to exchange their actual status or position and then try to solve possible conflicts by themselves. The agents need a negotiation scheme and a decision process that each agent uses to determine its positions, concessions and criteria for agreement [11]. A way of describing the negotiation is based on the assumption that the agents are economically rational. Agents create a deal that is a joint plan between the agents that would satisfy their goals. Each agent wants to maximize its own utility. The agents discuss a negotiation set, which is the set of all deals that have a positive utility for every agent.

2.6 Electrical Power Systems

An Electrical Power System can be defined as a group of one or more generating resources and connecting transmission lines operated under common management or supervision to supply consumers[13]. A power-delivery system is everything that exists between power generation (e.g. generators, batteries, etc.) and the specific consumer of power (e.g. computers, motors, weapon systems, etc.). A power-delivery system is formed by the Transmission system and the Distribution system. The transmission system efficiently transmits large amounts of electrical energy over long distances and at high voltage. When this high voltage electricity arrives at a major load center, the voltage is reduced to make the electricity more suitable to be sent to the individual consumers[13]. The Distribution System transmits electrical energy between transmission system and final user. An characteristic of Distribution systems is the use of a network with radial configuration (without loops), while the transmission system uses non-radial configurations for the network.

Obviously in a modern power delivery system (PDS) there are literally hundreds of devices, subsystems and controllers, etc, which are used to distribute, switch, control and make decisions about the health and functionality of the PDS itself. Power delivery systems are used in applications from ships and submarines to commercial buildings. The coordination process of these elements require sophisticated methods and technologies, as it is presented in [14]. The advent of power industry deregulation has placed greater emphasis on the availability of information, the analysis of this information, and the subsequent decision-making to optimize system operation in a competitive environment. Intelligent electronic devices (IEDs) being implemented in substations contain valuable information, both operational and non-operational, needed by many user groups within the utility. The challenge facing utilities is determining a standard integration architecture that meets the utility's specific needs, can extract the desired operational and non-operational information, and deliver this information to the users who have applications to analyze the information.

The work in [15] presents a multi-agent system that it consists of several Facilitator-Agents (FAGs), Equipment-Agents (EAGs) and Switch-Box-Agents (SBAGs). A FAG acts as a manager for the negotiation process between agents. EAG corresponds to an equipment of the electric power system such as a bus, a transformer and a transmission line, while SBAG is a pseudo-object which consists of neighboring circuit breakers and disconnecting switches. The proposed multi-agent system realizes appropriate switching operations by having agents interact with neighboring agents.

On other hand, the term Blackout refers to an effect that cause an entire power system to be de-energized. Several contingencies might cause the blackout such as: a)generator failure, b)damage to transmission lines or c)damage to device like transformers. The duration of the blackout can be minutes, hours or days. Obviously, the longer the blackout the worst its impact will be on the consumers. Power system restoration is the process necessary to reconfigure and r-energized the elements in the power system to restore service to as many consumers as possible [2]. After a system blackout, it is necessary to carry a restoration process to bring back the electric network into an operational (but perhaps degraded) state. To obtain the target configuration in a restoration process, various approaches have been proposed so far. These approaches can be roughly classified into four categories: heuristics search algorithms, expert systems (ESs), mathematical programming (MP), and soft computing [1].

Multi-agents system restoration, presented in [2], consists on a multi-agent approach to power system restoration process formed by a number of bus agents (BAGs) and a single facilitator agent (FAG). BAG is designed to decide a suboptimal target configuration after a fault occurs by interacting with other BAGs, while FAG is designed to act as a manager for the decision process. When a system portion is de-energized, the BAGs affected send a request to system FAG, and this chooses which BAGs request are accepted for restoration.

CHAPTER 3

Model Description and IPRs Network Architecture

3.1 Overview

The IPRs scheme attempts to quickly generate a system restoration solution through distributed coordination in a similar fashion to data routers in a Wide-Area Network.

3.2 Mapping of Electrical Energy Distribution Networks (EEDN) to a Wide Area Network (WAN)

A Wide-Area Network (WAN) is a computer network formed by a set of elements that can move data over geographically distant nodes [7]. When a flow of data needs to be established between two end points, these elements cooperate by moving pieces of data over the network until the data reaches the desired destination(s). Likewise, an Electrical power system is formed by a set of components interconnected in an electrical transmission and distribution network; this latter network is, in principle, similar to a Wide-Area Network (WAN) such as the Internet.

3.2.1 Network-flow problem

A Data networks is typically represented as a directed weighted graph. An important problem in this type of graph is the maximum flow problem. In this problem each edge represents a "pipe" that can transport some commodity and the weight of the edges represents the maximum amount that it can transport. The maximum-flow problem is to find a way of transporting the maximum amount of the given commodity from some vertex s, called the source to some vertex t, called the sink [16].

A flow network N consists of:

- A connected directed graph G with non-negative integer weights on the edges called "capacity".
- Two distinguished vertices, source(s) and sink(t) nodes, such that s has no incoming edges and t has no outgoing edges.

A flow for network N is an assignment of an integer value f(e) to each edge e of G that satisfies the following properties [16]:

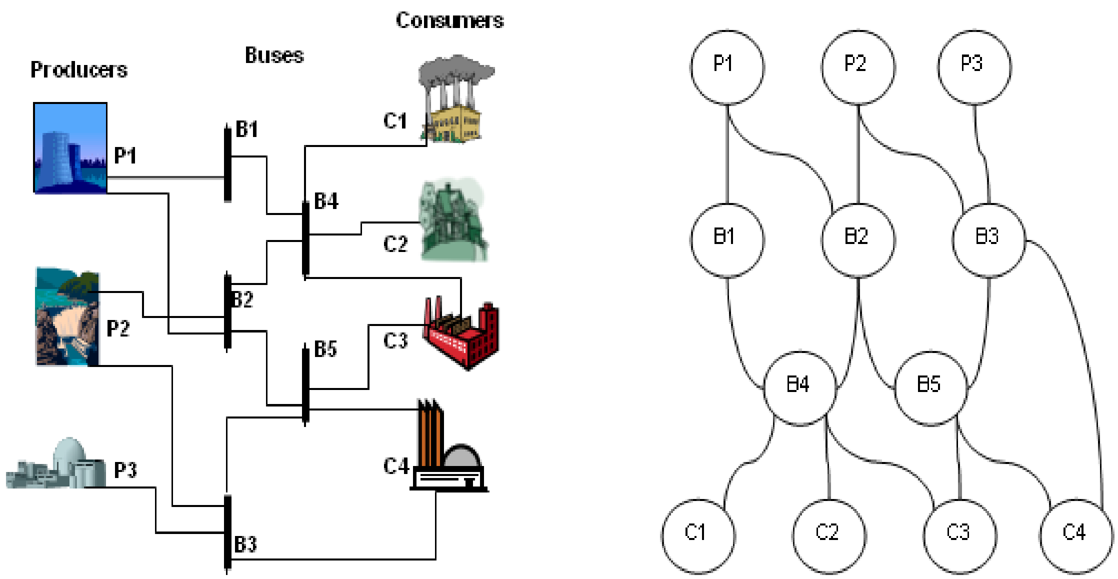
- For each edge e of G, the flow assigned must be no greater than the edges capacity (capacity rule).
- For each node v of G, the incoming flow must be equal to outgoing flow (conservation rule).

The restoration process for power systems can be represented as a Network flow problem and solved using graph theory as is presented in [17].

3.2.2 Similarities of an EEDN with a WAN

The fact that an EEDN and a WAN are formed by a set of elements designed to transmit a product (energy or data) from producers to consumers, permits us to establish a mapping between EEDN Elements and Computer Network Elements. Figure 3.1(a) shows the typical configuration for a EEDN, and figure 3.1(b) depicts a graph modelling the EEDN. We now present the roles for each of the components of an EEDN, and establish a parallel with a WAN:

- **Power Producers**: These are the elements in charge of generating electric energy. They can be nuclear generators, hydraulic generators, thermal generators or even an array of batteries. They are often called "**generators**" and they would be the equivalent of data servers in a WAN. In a network flow graph representation the producer are the source nodes.
- **Power consumers**: The consumers are the clients of the electrical system such as hospitals, office building, malls, etc. They are typically called the "loads" and they would be the equivalent of client applications. In our network graph representation the loads are the sink nodes.
- **Transmission/Distribution lines**: they are in charge of transferring electrical power from producers (generators) to consumers (loads). In a WAN these components would be data links. In a network graph representation the Transmission lines are edges and the power flow direction is the direction of the edges.
- **Buses**: They are a set of internal nodes which the electrical transmission lines are connected to. In a WAN, buses would be equivalent to data routers and data switches. In a Network flow graph, buses are internal nodes in the graph.



(a) EEDN distribution (b) EEDN Graph representation

Figure 3.1: Modeling a EEDN as a graph

3.2.3 Operation in WAN

When a data client sends an information request to a data server, this server fragments the data requested in packets and they are sent to the client across the network. The packets are the basic unit of data that can be transmitted on a computer network [7]. At each step of this process, a router that receives a data packet determines the next router that shall forward that fragment of data until the data reaches the desired destination(s). Notice that there might be many candidate routers, but the one that can do the best forwarding job is the one that is selected.

If any router or link of the system fails, the routers will re-configure the paths to route the packets, so that the clients are not affected by such failure. In our view, a EEDN could operate in similar fashion with due consideration of the physical differences between data exchange and energy exchange.

3.3 Assumptions for Restoration Process using IPRs

The Power system failures may be caused by storms, failures of the protection system, failures of high-voltage equipment, excessive customer demand, human errors, sabotage (vandalism or terrorism) and other major disturbances [2]. Power system restoration problem is a very complex combinational problem that can be formulated as a multi-stage, non-linear, continuous and binary constrained optimization problem. The main objective of this process is to restore service to loads as quickly as possible keeping a feasible configuration in all stages[18].

Currently, the power system restoration process commonly consists of two main sequential steps. First, the optimal system configuration target is obtained from the set of feasible configurations. Second, switching operations are performed in order to achieve the optimal target configuration obtained in the first step, maintaining the system operating within its feasible limits[18]. That means all bus voltage magnitudes, transmission line flows (active and reactive power), and generator power outputs are within their corresponding feasible limits [18].

In this thesis, we assume the power system restoration problem as a Network Flow problem where the commodity in the network is only the active power. The other aspects involve in a standard power system restoration, such as voltages, system frequency and reactive power, are not involved into negotiation scheme proposed for IPRs in this thesis. Likewise, the negotiation process performed by IPRs will not include the switching operations order. All these issues are considered as elements of the future works.

3.4 Mathematical formulation for System Restoration

The first step to apply Computer Science to a power restoration problem is to understand that power restoration is an optimization problem, and it has an objective function with a set of associated constraints. Our mathematical model is a modification of a mathematical formulation presented in [2].

3.4.1 Objective function

The objective of the mathematical model of this power system restoration approach is to maximize the number of served loads with the highest priority. In other words, after a fault occurs, the model shall seek to restore as many of the most important loads as possible. In this scheme, each load L_k has a priority Pr_k, which is a number in the range [1, M]. This number indicates the relative priority of a given load with respect to other loads in the system. Priority values close to 1 indicate high-priority, whereas values close to M indicate loads with relatively low priority. The objective function is given by the following mathematical expression:

$$Max \sum_{k \epsilon R} L_k * y_k * (\alpha - Pr_k)$$

Where Pr_k is the load Priority (the highest priority load will have Pr = 1, the second priority load will have Pr =2 and likewise the other loads), α is a natural number larger than the Pr value of less priority, L_k is each load in the system, y_k is a decision variable ($y_k = 1$: load L_k is Restored, $y_k = 0$: load L_k is not restored), and R defines the set of de-energized loads. Our goal is for our algorithms to attempt to restore as many priority-1 loads as possible without violating any constraints. Then, move to the priority-2 loads and restore as many as possible. The restoration continues until either all priority classes have been explored or no more power is available to bring any other load back into the system.

3.4.2 Model constrains

The constraints associated with our mathematical model are similar to the constraints in the restoration model presented in [2]:

- **Power balance of the system between supply and demand**. A typically EEDN does not have buffers for storing energy because energy buffers are not cost-effective; then, all power generated must be consumed by the loads. In mathematical terms: the sum of power generated by the system must be equal that the sum of the power consumed by all the loads (loads in normal state and restored after blackout). This constraint is defined by:

  $$\sum_{k \epsilon M} G_k - \sum_{k \epsilon R} L * x_k - \sum_{i \epsilon N} L_i = 0$$

  Where G_k is the power generated by generator k, L_k is Power demanded by load k, x_k is a decision variable ($x_k = 1$: included in restoration path, $x_k = 0$: no included), L_i is Power demanded by load i, R is the set of load for restoration operation, N is the set of load in normal state and M is the set of generators in the system.

- **Limits on power source available in each bus for restoration.** For each node of the system, the flow of power in output lines cannot be greater than the sum of power available in input lines. In other words, a node can not give more electrical power that it can receive. This constraint is defined by:

  $$\sum_{e \epsilon F_q} P_e * x_e \leq G_q(q \epsilon S)$$

  Where P_e means Power flow in branch e, x_e is a decision variable for line e ($x_e = 1$: included in restoration path, $x_e = 0$: not included), G_q represents the Power available in bus q. F_q: branches connected to bus q and S is the set of buses in the system.

- **Limits in line capacity for power transmission.** For each line in the system the power flow cannot be greater than the line capacity, independent of flow direction.

$$| P_k | \leq U_k (k \epsilon B)$$

Where P_k is power flow in line k, U_k is power flow capacity of line k and B is set of all lines at the system.

3.5 IPRs Network Architecture

The key of our approach is that the IPRs are aware of the system state at all times. We assume that there is one IPR in each of the buses in the system so they can be always monitoring the system lines. In addition, there are special purpose IPRs associated with the power generators and with the loads. We assume that we are dealing only with a transmission system, but our ideas also apply to a distribution system. Figure 3.2(a) shows a system with four buses, three generators and two loads. Figure 3.2(b) shows the IPRs that correspond to this configuration. Each IPR has a set of output lines that connect the IPR to other IPRs or to loads. Likewise, each IPR has a set of input lines that connect the IPR to other IPRs or to generators. These output and input lines correspond to transmission lines that move power between the buses associated with each IPRs. Input lines model a transmission line than brings power into the bus associated a given IPR. Likewise, output lines model a transmission line (or branch) that feeds from the bus associated with a given IPR.

The IPRs are organized in a peer-to-peer network, or a mesh architecture, as shown in figures 3.2(a) and 3.2(b). In this architecture, for a given IPR, it is irrelevant whether its inputs come directly from power producers or other IPRs. The key to our approach is to provide multiple redundant power paths between producers (generators) and consumers (loads).

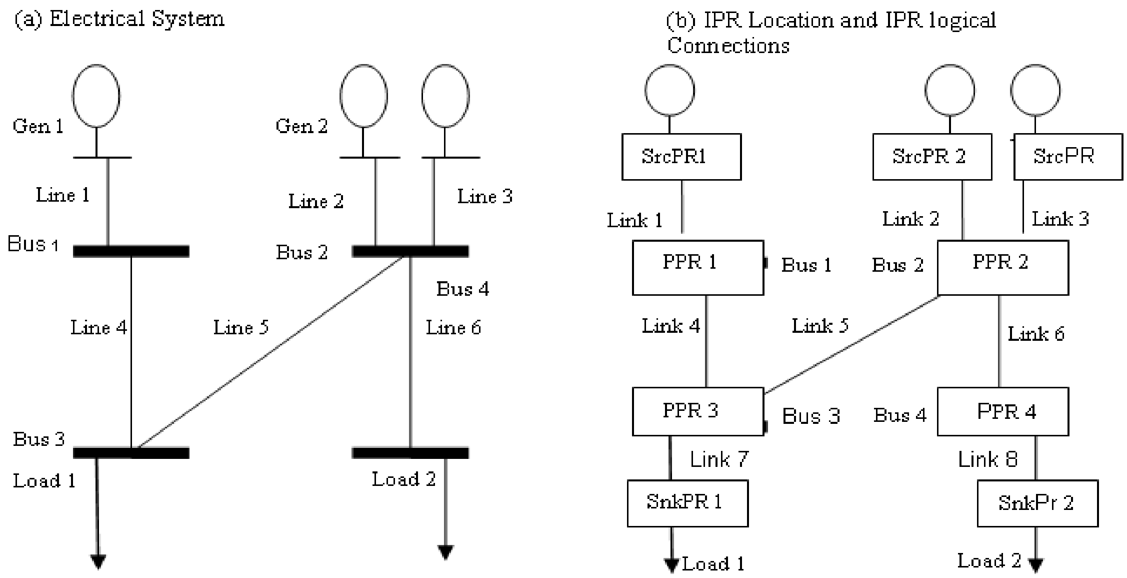


Figure 3.2: Relation between EEDN, IPRs location and IPR logical connections. (Gen n: Generator n, SrcPR: source Power Router, PPR: Principal Power Router, SnkPR: Sink Power Router)

In addition, an important issue to realize is that the network for transmission of electrical energy is different from the communication network between IPRs. This scheme guarantees independency of communication in light of a contingency in the electric transmission system. But, the IPR network communication must emulate the electrical connections in the system. To accomplish this, each IPR X establishes a TCP/IP connection with each of the IPRs Y that are attached to lines associated with IPR X. This is shown in figure 3.2(b).

3.5.1 Classification of IPRs

We have developed three types of IPRs as shown in figure 3.2(b):

- **Source Power Router (SrcPR)**: These routers are located at power generators (producers), and they inform the system about the capacity of their power generators. In addition, each one communicates with its neighbors about its current status at particular moment.

- **Principal Power Router (PPR)**: these routers will re-configure the network in the event of a high-risk operating condition, or some type of system failure.
- **Sink Power Router (SnPR)**: These routers are connected between the IPRs network and the loads. Their principal function is to connect and disconnect loads from the system as required.

3.6 IPRs Decision Scheme

IPRs decisions for the activation of contingency plans are based on two factors; next, we discuss each one:

- **Priority Factor**: Every output line has a priority factor, similar to the priority values assigned to the loads. These priority factors indicate which are the lines that must be serviced first, in the event of a contingency. All IPRs must respond and guarantee satisfaction to their "clients" attached to with highest priority. The priority factor of an output line is defined in the range of Natural numbers in which one 1 means the highest priority, and larger priority factor values indicate less priority. For example, a line with priority factor 6 is less important than a line with priority factor 2. Initially the priority factor of each line is set by the system operators. In the future, we propose to explore algorithms that assign priorities based on a function of the types of loads that are fed (directly or indirectly) by each output line.
- **Reliability Factor**: Every input line has a reliability factor, which indicates how reliable is the source of power feeding the line. Notice that a given input line S feeding an IPR X is seen as an output line by another IPR Y. Hence, the reliability factor of an input line S is equal to the priority factor assigned to the line by the IPR Y that sees the line S as an output line.

3.7 IPR Basic Negotiation Scheme

The main operational behavior for the IPRs is based on two ideas:

- When an IPR receives a power request, it verifies the priority of the "client" output line that made the request. If the client has the highest priority factor, then the IPR tries to resolve the request. Otherwise, the IPR: a) sends a status request to all client output lines with higher priority factor, b) waits for status responses, and c) the IPR tries to resolve all received request beginning with the request with highest priority.
- For each request, the IPR first sends a request for more power to the more reliable input line available. If the response obtained is a Deny Response then the IPR proceeds to send the request to the input line with the second highest reliability. This process is repeated until power is received or all lines have been explored.

3.7.1 Basics algorithms for IPRs Negotiation scheme

The operational behavior of IPRs described above, is implemented using the following algorithm, which is divided in three parts:

1. The first part is applicable for the Sink PR:

```
If restoration process is needed then
    Each load affected sends a
    get message to IPR with most reliable line
    If not satisfied, try next line until
    power arrives or request is denied by all
    neighboring IPRs
End if
```

2. The second part is applicable for each PPR:

```
If IPR receive a request message then
    Check source message priority
    Store the message in request queue
    Send a Status Request to all other clients
    with higher priority asking for their status.
    Wait time T to acquire responses.
    For each response
        If response is not normal status
            Store the message response in request queue
        End if
    For each message in request queue
        Move to first Input Link
        Repeat until an OK response is obtained or a
        deny message is obtained from all power suppliers
        Adjacent IPR
            Check Link capacity
            If link capacity can support more power flow
                Send get message to IPR with most
                reliable line not yet inspected
                Wait for response
                If OK response
                    Send Ok response to client
                else
                    Move to next Input Link
                End if
```

```
                If IPR obtains deny message from all IPRs
                    Send deny response to client
                End if
            else
                Move to Input Link
            End if
       End repeat
  End if
```

3. The third part is applicable for each Source PR:

```
If IPR receives a get message then
    If the generator can generate more power
        Send one OK response to the client
    Else
        Send a deny message to client
    End if
End if
```

3.7.2 Example of basic IPRs Negotiation

We use the system presented in figure 3.2 (a) to show how the IPRs network interacts to perform the system restoration process. For this system, we propose to put an IPR in each bus of the system. In normal state, the IPRs interchange information about their status and their line status.

In our approach each bus has Principal Power Router (PPR), each Load has a Sink Power Router and each Generator has a Source Power Router (SrcPR)(figure 3.3(b)). When a fault occurs, in this case Load 1 is un-served because Line 1 has a failure (figure

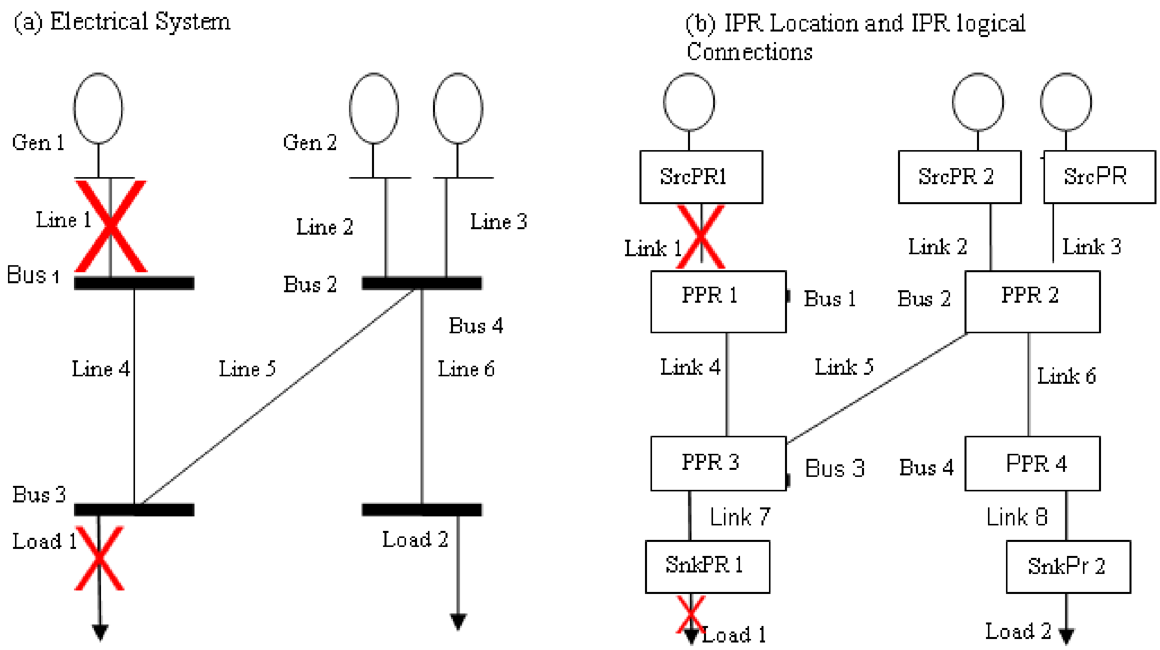


Figure 3.3: Load 1 is un-served because Line 1 has a failure

3.3(a)), the restoration process is performed as follow:

1. The affected Sink Power Router begins the restoration process (SnkPR 1). This Sink IPR sends a request message to its most reliable supplier in this case PPR 3 (figure 3.4(a-1)).

2. The PPR3 sends a request message to its most reliable supplier, PPR1 (figure 3.4(a-2)) .

3. PPR 1 cannot service the request, so it sends a Deny Message to PPR3 (figure 3.4(a-3)).

4. The PPR 3 receives the deny message and it proceeds to send a request message to the second most reliable supplier, in this case PPR 2 (figure 3.4(a-4)).

5. The PPR 2 receives the request message, it sends a Request Message to its most reliable supplier SRCPR 2 (figure 3.4(a-5)).

6. SRCPR2 answers with an affirmative response that is routed to all involved IPRS until reaches the Sink IPR that began the restoration process (figure 3.4(a-6)(a-7)(a-8)) .

7. Finally, the system goes back into an operational state with its all Loads served as figure 3.4(b) shows.

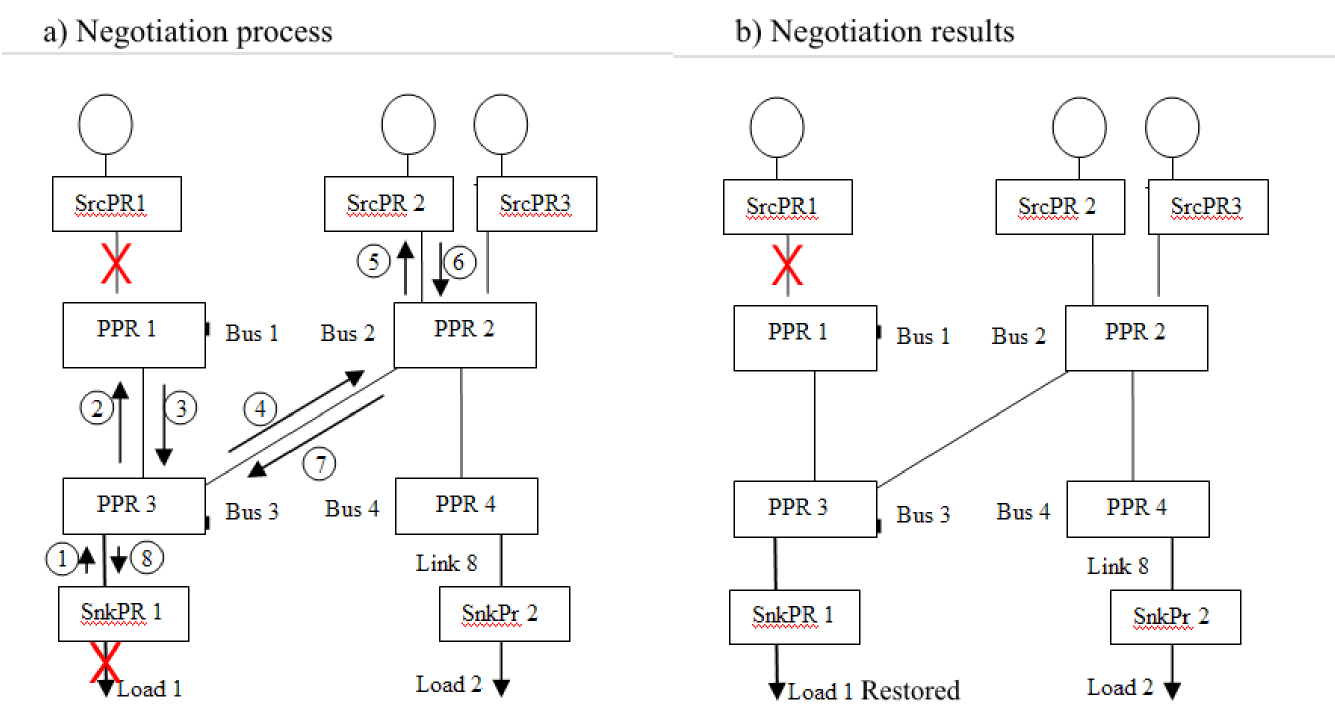


Figure 3.4: Example of IPRs Negotiation Process.

3.7.3 Improvement to Basic Negotiation Scheme

The principal advantage of IPRs Basic negotiation scheme is that it is simple, thus easy to implement. Using this scheme the IPRs obtain quickly response to their requests.

But, in this scheme, the IPRs only can answer with an OK response if one of its Input Lines can serve the entire request, otherwise, the IPR sends a Deny Response for this request. For example, in the system shown in figure3.5 a) the Load 1 is un-served after a blackout. The IPRs perform the restoration process as follows:

1. The SnkPR 1 with 100 MW sends a request for service to PPR 1 (figure3.5 (b-1)).
2. PPR 1 has two input lines with 50 MW of capacity. PPR 1 answers with a Deny response because none lines can support the 100 MW (figure 3.5 (b-1).
3. Finally, the Load 1 still un-served after IPRs negotiation process as shown figure 3.5 (c).

But, the system can serve Load 1 if the request is split into two request of 50 MW. To avoid this problem, we made a modification in the IPRs Negotiation scheme that we discuss bellow.

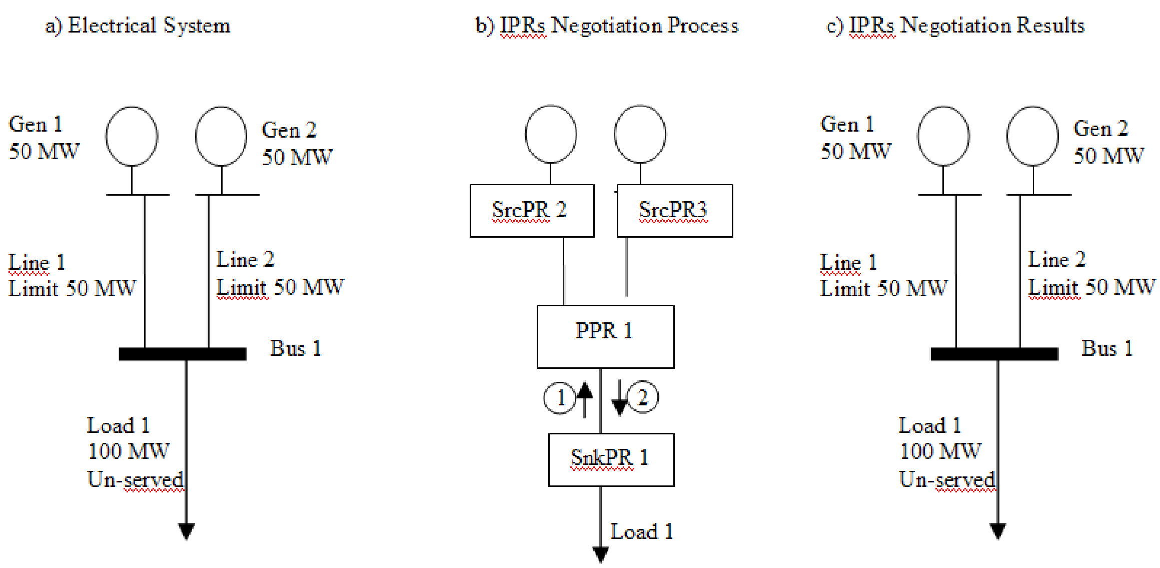


Figure 3.5: Disadvantage of IPRs Basic negotiation scheme

3.7.3.1 Modifications to Improve the IPRs Negotiation

We modified the Basic Negotiation scheme of the IPRs to solve this problem and improve the negotiation results. This improvement consists in two modifications:

- When an IPR receives a Deny response from all Input Lines, it proceeds to send request through its output lines that do not have assigned flow. And these output lines become into Input lines.
- When a given IPR receive Deny Response from all Input Lines, it split the request into many requests as necessary and it sends these requests through the Input Lines.

3.7.3.2 Example of the new Negotiation scheme

Using the system depicted in figure 3.6 we explain the new negotiation scheme. In this case, Load 1 is un-served after a blackout. The restoration process is performed as follows:

1. Snk PR1 sends a requests message to PPR 1 (figure 3.6 (b-1)), PPR 1 checks its input lines, but none of the input line can hold the request.
2. PPR 1 checks the output lines looking for any output that can hold the request. But, it does not find any line.
3. The request is split into two request of 50 MW and they are send through Line 1 and Line 2 (figure 3.6 (b-2)).
4. Src PR 1 and Src PR 2 allocate resources and response to PPR 1 (figure 3.6 (b-3)).
5. PPR 1 gets the responses and sends a OK message to Load 1 (figure 3.6 (b-4)).
6. Finally, Load 1 is restored as shown in figure 3.6 (c).

3.7.4 Disadvantages of modification of IPRs

With this modifications the IPRs have more possible paths to supply power to the loads, but with this new universe of possibilities the number of messages travelling across the network increases too. This new scenario, with so many messages, generates congestions

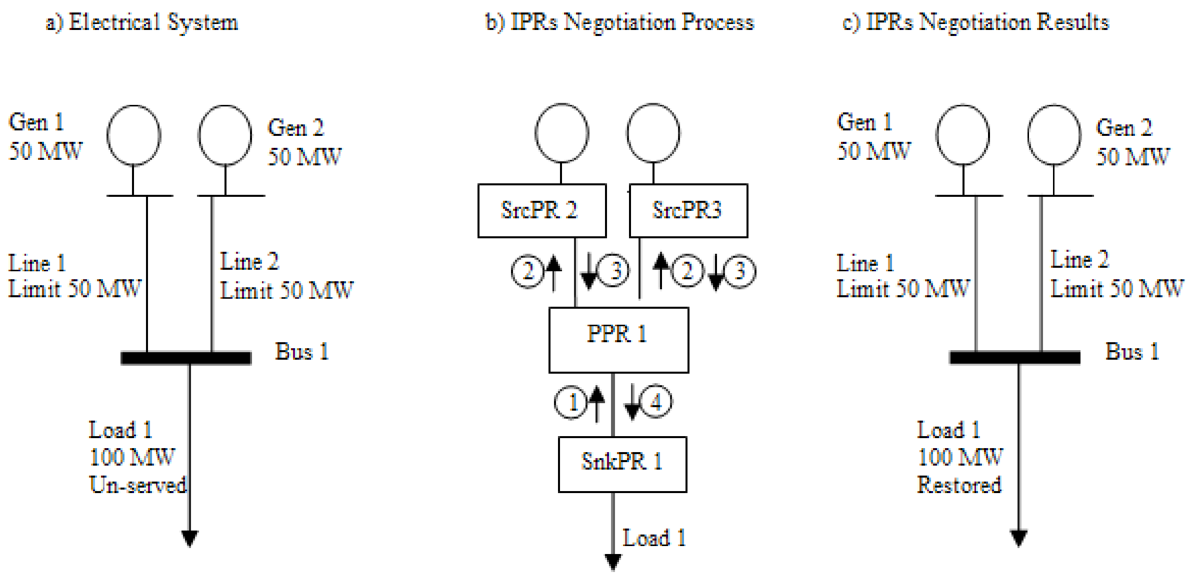


Figure 3.6: Example of the IPRs Negotiation scheme modified

on the network. To avoid this problem, we present in the next chapter a multi-stage scheme for controlling the number of message in the network.

CHAPTER 4

Multi-stage IPR Negotiation scheme

4.1 Overview

In this chapter we introduce the Island-zone approach for controlling the number of message travelling on the network. In this approach the system is divided in several zones. Each zone is a sub-system with generators, buses and loads that need be restored. Likewise, we present the protocols and algorithms to perform the negotiation process in two phases. The First phase is for restoring the loads with generation capacity available in the same zone, and the second phase is for restoring loads using the capacity in the neighboring zones.

4.2 Island-zone approach

The key to improve the performance and quality of the IPRs decision making resides in their knowledge of the state of their neighbors. Hence, they must exchange state messages continuously. But, as the IPRs Network grows the number of messages will grow too, generating congestion in the communications network as we found in some experiments using IPRs modified scheme. To avoid this, we divide the system in zones or geographical regions. Each zone has a balance between generation and demand. Then, each zone behaves as an autonomous network of IPRs, capable of exchanging messages with other zones.

4.2.1 Types of IPRs

To support this Zone approach we need an additional IPR classification scheme. Interior IPRs are those that exchange messages within a zone. Border IPRs exchange messages between zones. Figure 4.1 shows an example of a Power System divided in two zones (A and B). Zone A has seven buses and on each bus has an IPR. Zone A has six interior IPRs and one Border IPR. Likewise, Zone B has 11 buses with nine Interior IPRs and two border IPRs.

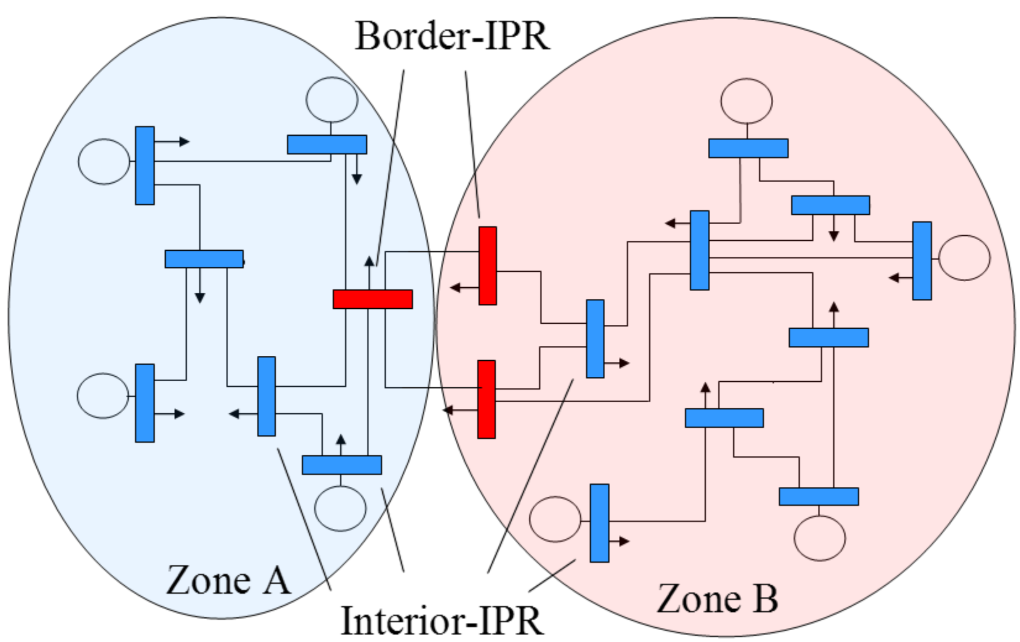


Figure 4.1: Example of Island-zone approach

- **Interiors IPRs.** They exchange Intra-zone messages. Their main function is to establish a secure operational state within the interior of each Zone. For this, each SrcPR informs the state of its generator in a message that is spread to the interior of the zone. In this way, each IPR knows the state of generators in its area, allowing it to modify its reliability table to request power from generators with more probability of responding its request. This scheme avoids the waste of time in asking for power from generators that can not satisfy them.
- **Border IPRs.** They exchange state messages between different zones to maintain the well-being of the general state of the system. When in a zone X, there is a demand that cannot be served by its generators, the border IPRs request power to their neighboring zones in an effort to guarantee that the entirety of the loads in zone X are served. In the event of a catastrophic event that forces to the division of the systems in islands, the border IPRs exchange messages to coordinate the interconnection process among those islands.

4.2.2 Zones as Power Network Equivalents

In Electrical Power System a Network Equivalent is a form for representing a region of the power system as a Generator or a load depending on the power balance in this region. For a given power system region, if the Generation capacity exceeds the demand then this region will be represented as a Generator; otherwise, the section will be represented as a Load.

To simplify the negotiation schema, Border IPRs see each neighboring zone as a Generator or Load (Network Equivalent) depending on the power flow direction. Figure 4.2 illustrates this idea; it shows the view of Zone A for Border IPRs of Zone B as two Generators and two Loads. These Generators are the least reliable generators for Zone B.

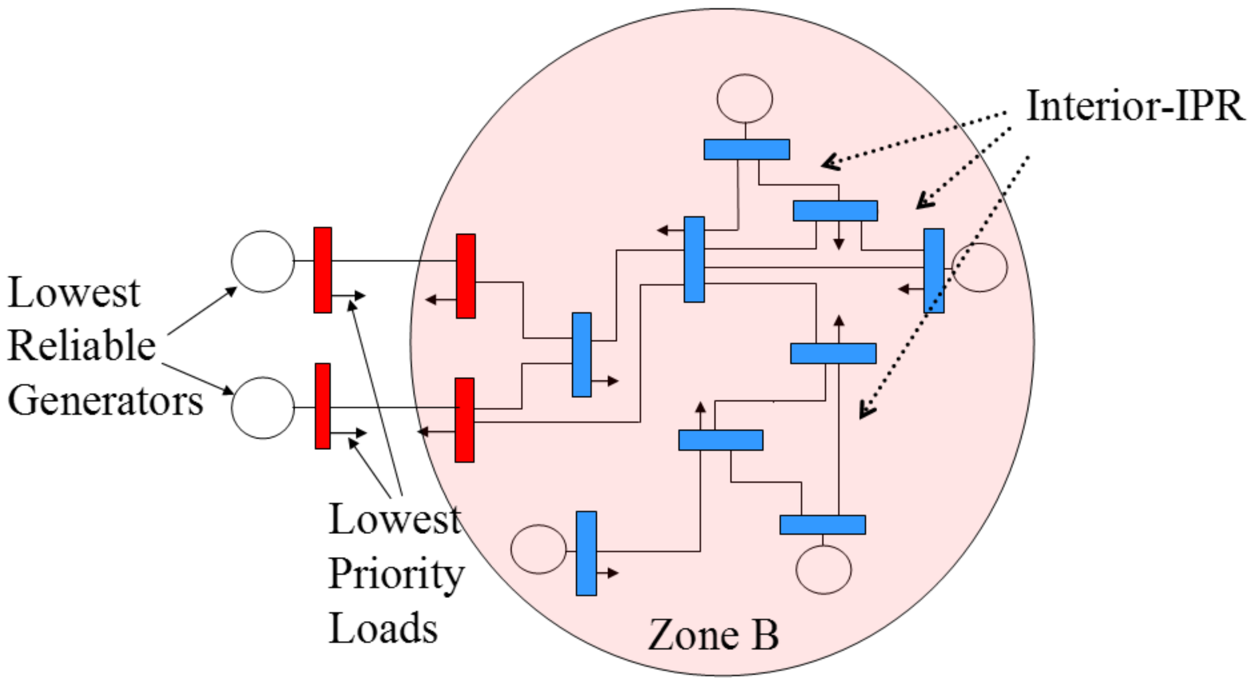


Figure 4.2: Network equivalent of zone A for zone B 4.1

4.3 Negotiation in two phases

Clearly, it is almost impossible to obtain optimal answers starting from local decisions. And although that it is not our objective, the IPR they will have the capacity to improve the status of the system by means of a negotiation in several stages looking to restore more and more loads as time progresses. In this section we present a description of each negotiation stage. In Appendix A we present the complex algorithms to implement this multi-stage negotiation scheme.

4.3.1 Intra-Zone Negotiation phase

The first phase of IPR negotiation is performed at the intra-zone level. At this stage, the Interior IPRs work to satisfy the maxim number of high-priority loads to the interior of its zone. By means of a periodic exchange of messages, the interior IPRs are able to determine which loads should be served with the generation capacity in each zone, to make sure that the system operates in a secure way. The process of intra-zone negotiation is carried out in three stages, discussed below:

4.3.1.1 Friendly Request stage.

This is the first stage of the IPRs Negotiation process to perform the system restoration. The goal of this stage is return the system to its previous operational state, maintaining the power flow as it was before the blackout. In this stage of the negotiation the IPRs follow the normal outline of negotiation described in section 3.6. In this scheme, each load uses its SnkPR to pose requests for power to the IPR network. This request is routed until an affirmative answer or negative answer is found, which depend on current system conditions. Following the priorities scheme, IPRs choose which loads can be served and which cannot. In this phase the IPRs try to return the system to its previous operational state, maintaining the request it the same direction as power flows were before the contingency.

But, if a high priority load sends a late request and the resources of the system are already assigned and they do not allow serving this load, this load will receive a negative answer. Thus, in this phase loads of high-priority might be unserved. Since IPRs only request energy based on the flow of the previous stage, then alternative flows cannot be explored. As a result other solution that might enable a high-priority load to be restored are not considered.

Example of Friendly Stage.

In this example the system has three generators, three loads and nine buses. In this case, the power flows in steady state is like figure 4.3. After a system blackout caused by failures in the lines 2-8 and 4-1, the IPRs begin the restoration process. The first

Negotiation stage is the Friendly Stage with the objective of returning the system to its previous status. The Friendly Request stage is performed as follows:

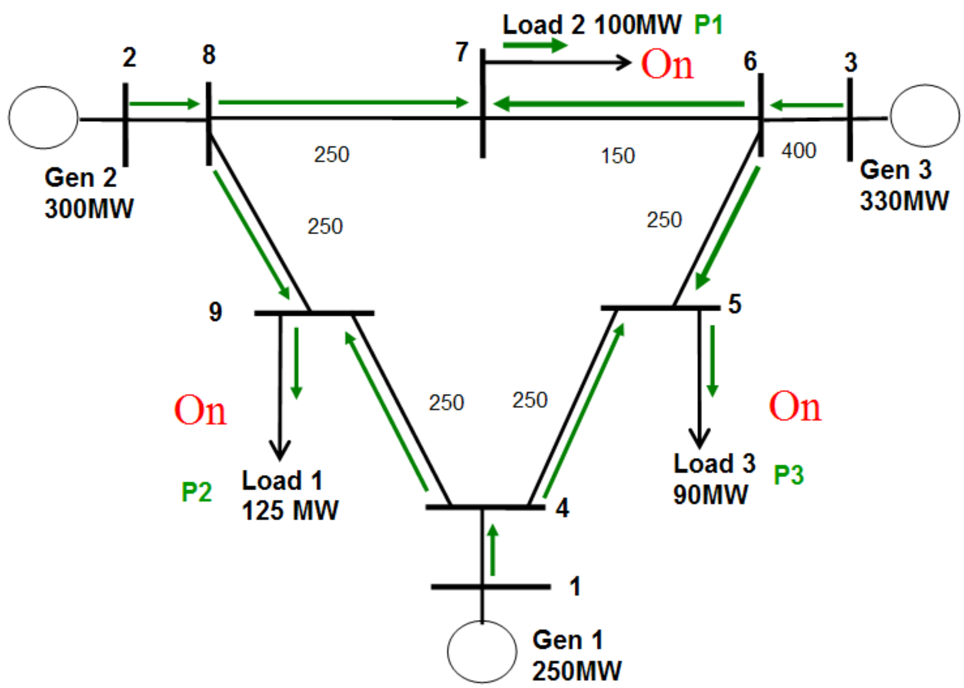


Figure 4.3: Example of Friendly stage. Power flows in steady state

1. Loads 1, 2 and 3 send Request Messages using its respective Sink Power Routers (figure 4.4 (1)).

2. The message are routed across the network using the scheme described above using priority and reliability factors (figure 4.4 (2)).

3. PPR 7 and 5 receive an Affirmative Response and these responses are routed to SnkPr 2 and 3 (figure 4.4 (3)).

4. PPR 9 receives a Deny message from its Input Lines (figure 4.4 (4)), and it routes this response to SnkPr 1 (figure 4.4 (5)). Notice that the request sent by Load 1 only reach IPR4 and IPR8 because the lines 4-5 and 8-7 are outputs of IPR 4 and 8, since in the friendly stage the requests are transmitted only across input lines.

5. As result of this stage load 2 and 3 are restored, but load 1 remains disconnected.

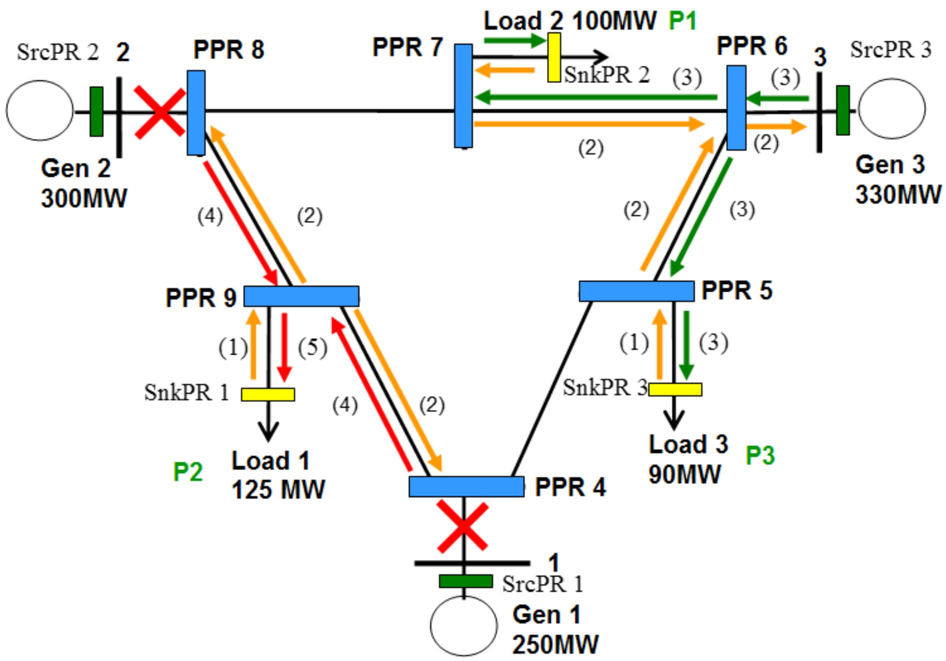


Figure 4.4: Example of Friendly stage. Restoration process

4.3.1.2 Persistent Request stage.

This is the second stage performed by the IPRs to restore the system, and it is performed after Friendly stage if one or a set of loads remain un-served. The objective of this stage is restore the loads that could not be restored during the Friendly Stage. The SnkPRs that receive a negative answer in the Friendly Request stage now send a Persistent Service Request. This request type forces the IPRs to attempt a system reconfiguration by changing the direction of the power flows necessary to satisfy the most high-priority loads. In this stage, if it is necessary the IPRs use the split request scheme described in section 3.6.3.1.

Example of Persistent Stage.

The system for this example is the same used in the example of Friendly Stage with three generators, three loads and nine buses. In this case, the power flows in steady state is as shown figure 4.3. After a system blackout caused by failures in the lines 2-8 and 4-1, the IPRs begin restoration process. The first Negotiation stage is the Friendly Stage with the objective of returning the system to its previous status. After Friendly Stage the Load 1 remains disconnected, then the IPRs begin the Persistent stage to supply the load 1. The Persistent stage is performed as follow:

1. Load 1 sends a Persistent Request using its respective Sink Power Routers (figure 4.5 (1)).

2. The message is routed across the network using the Persistent stage scheme (figure 4.5 (2)). Notice that the request can be sent by PPR 4 through the line 4-5 because in this stage the requests are transmitted across the output lines that do not have power allocated.

3. The final response is routed from SrcPR 3 to SnkPr 1 across the network (figure 4.5 (3)).

4. As result of this stage load 1 is restored like load 2 and 3.

4.3.1.3 Load shedding communication scheme.

This is the last stage of intra-zone negotiation phase. In this stages the IPRs determine if they need to disconnect a set of low-priority loads to guarantee service to high-priority loads.

When a given IPR determines that it needs to disconnect a set of low priority loads to guarantee service to a high priority load, it sends a special disconnect message to the selected low-priority loads. To accomplish this, every request message is signed with a complete route to the load. The IPR, wich can be the Source or the Principal Power Router, sends a Disconnect Message following the path stored in the message to reach the SnkPRs servicing the low-priority loads. The IPR then waits for a Disconnect Confirmation

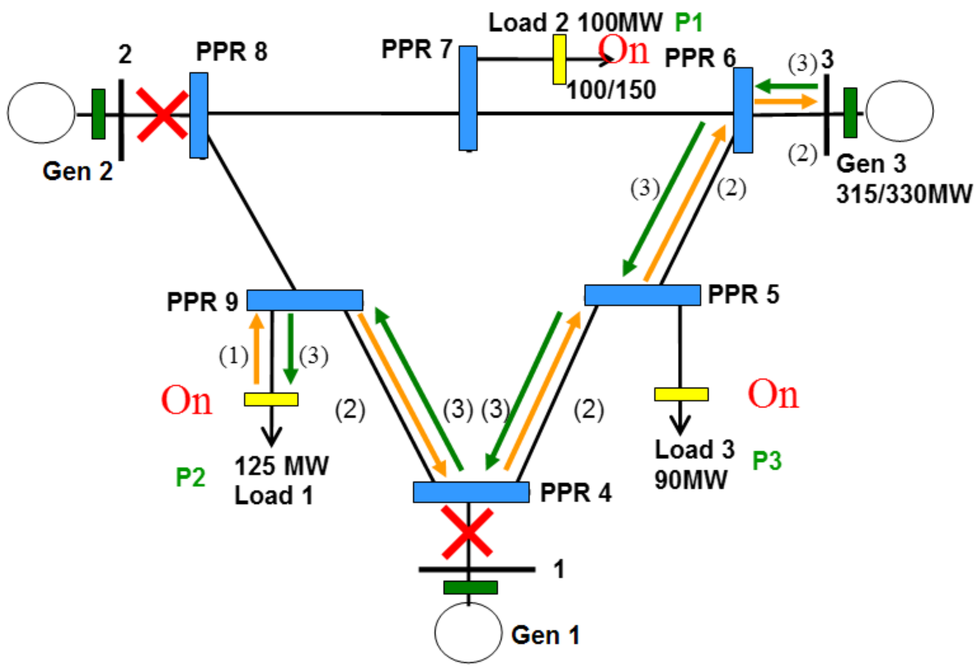


Figure 4.5: Example of Persistent stage. Restoration process

Message. This latter is routed by the IPRs in the path between the IPR and the SnkPRs. When the SnkPR gets a Disconnect message, it disconnects its load and sends a disconnect confirmation message to IPR that sent the Disconnect message. Then, the SnkPR starts looking for power from alternative generators. When the SrcPR receives the disconnect message from all disconnected loads, it send an affirmative response to the high priority load that made the power request.

Example of Persistent Stage.

The system for this example is similar to the system used in the example of Friendly Stage with three generators, three loads and nine buses. But in this case the Generator 3 only can serve 270 MW. The power flows in steady state is as shown in figure 4.3. After a system blackout caused by failures in the lines 2-8 and 4-1, the IPRs begin restoration process. The first Negotiation stage is the Friendly Stage with the objective of return the system to its previous status. In this case, the Load 1 with priority 2 are not served while

Load 3 with priority 3 has been served. Then the IPRs begin the persistent negotiation stage with load shedding. The Persistent with load shedding stage is performed as follow:

1. Load 1 sends a Persistent Request using its respective Sink Power Routers (figure 4.6 (1)).

2. The message is routed across the network using the Persistent stage scheme (figure 4.6 (2)). Notice that the request is sent by PPR 4 through the line 4-5 because in this stage the requests are transmitted across the output lines that do not have power allocated. And SrcPR 3 receives the request and notices that it does not have enough capacity to supply all loads. This SrcPR notices that the new request is from a 2nd priority load and it is serving a 3th priority load, so it decides to disconnect the lowest priority load.

3. SrcPR 3 sends a Disconnect message to SnkPr connected to Load 3 (figure 4.7 (3)) . This message is routed until it reaches SnkPR 3 (figure 4.7 (4)).

4. SnkPR 3 disconnects Load 3 and sends a Disconnect confirmation to SrcPR 3 (figure 4.7 (5)). This message is routed until it reaches SrcPR 3 (figure 4.6 (6)).

5. SrcPR 3 sends the Affirmative Response to SnkPR 1 and this message is routed across the network until it reaches SnkPR 1 (figure 4.8 (7)).

6. Finally, Load 1 with priority 2 is served like Load 2 with priority 1, while Load 3 is disconnected.

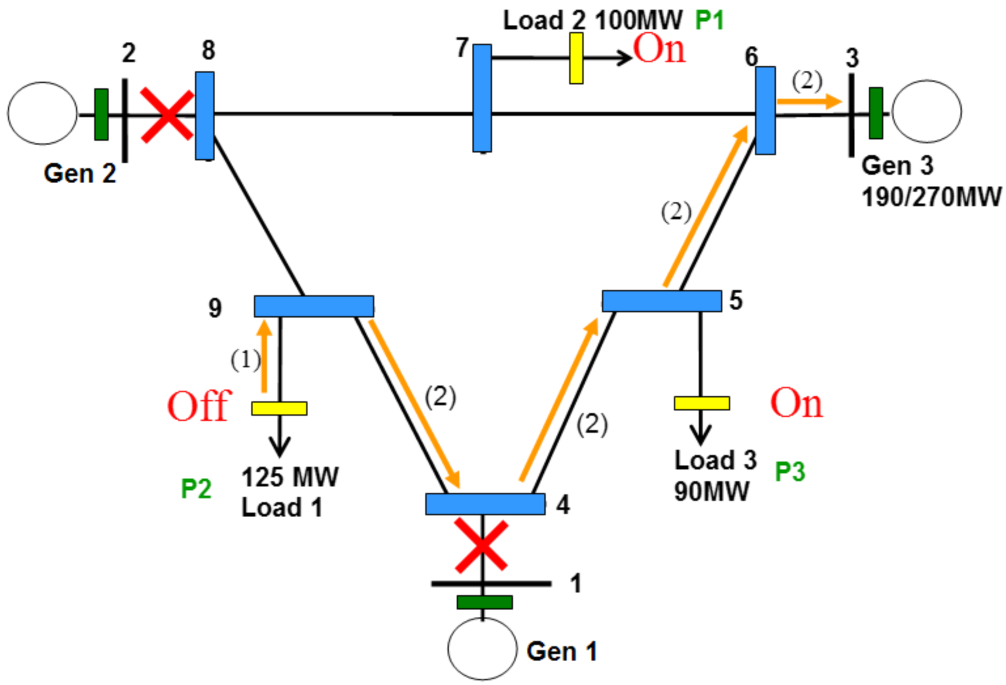


Figure 4.6: Example of Load Shedding. Restoration process - section a

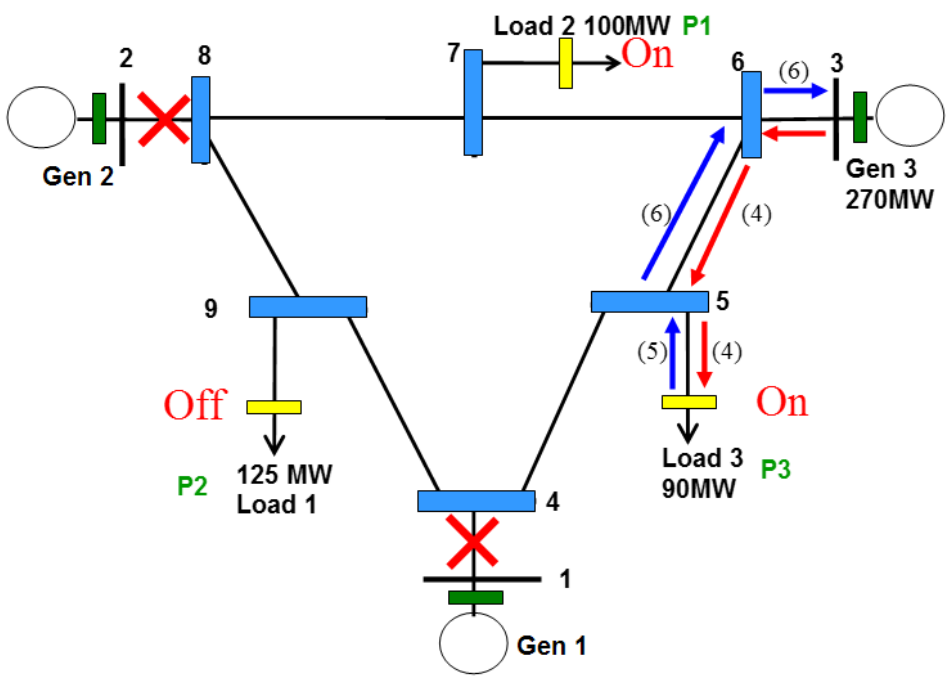


Figure 4.7: Example of Load Shedding. Restoration process - section b

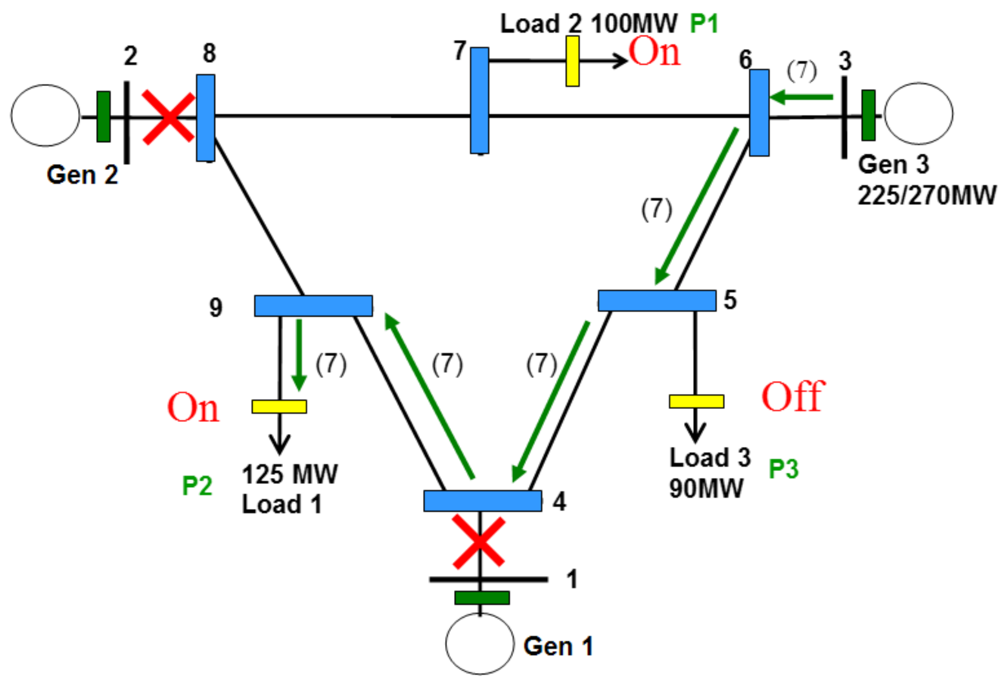


Figure 4.8: Example of Load Shedding. Restoration process - section c

4.3.2 Inter-zone Negotiation phase

The objective of this phase is to get power from another zone to try to restore the loads that were not served in the Intra-Zone negotiation process. When a SnkPR receives a denied response for a Persistent Request Message, it sends a Inter-zone Assistance Request, and this message is routed until it gets a Border IPR. This Border IPR sends this request to its peer Border IPR in another zone. Then, if a Border IPR receives an Inter-Zone Request, it stores this message and it sends a Friendly Request Message to the IPRs in its zone network. Notice that this message is treated as an Intra-Zone message and it is processed as mentioned in the previous section.

When the Border IPR receives the final response, it is sent to the border IPR in the zone which initiated the negotiation process. If this message is an affirmative response, it is sent to the SnkPR that made the original request. Otherwise, the original power Request is routed to another Border IPR until an affirmative response is obtained, or a Deny response is obtained from all Border IPRs. In this latter case, a final Deny Response is sent to the SnkPR that made the original request. This Snk awaits a time interval T, and then begins the whole process again.

Example of Inter-zone negotiation Phase

The system used in this example is divided in two zones, each one has three generators, three loads and nine buses as shown in figure 4.9.

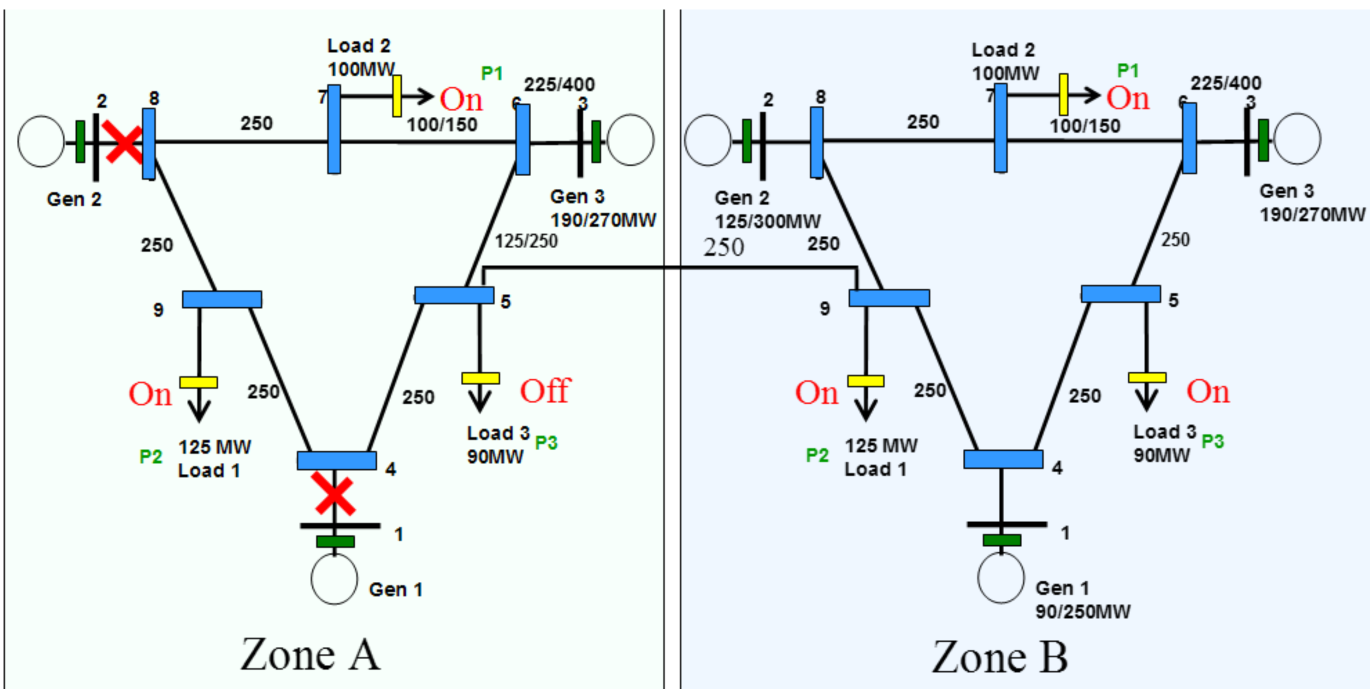


Figure 4.9: Example of Inter-zone Negotiation. System conditions

After a system blackout caused by failures in the lines 2-8 and 4-1 in Zone A, the IPRs begin the restoration process. The first Negotiation phase is performed at Intra-zone level. As result of Intra-zone Negotiation in each zone, all loads of Zone B are restored while Load 1 and 2 of Zone A are restored but Load 3 is disconnected. The system uses the Inter-zone negotiation to restored load 3 of zone A. This process is performed as follow:

1. Load 3 of zone A is un-served after an intra-zone negotiation, it sends a request for inter-zone assistance (figure 4.10 (1)).
2. This request is routed to the Zone B using Border-IPR 5 in Zone A (figure 4.10 (2)) .
3. Border-IPR 9 of Zone B, catches the request and begins an intra-zone negotiation to satisfy the request (figure 4.10 (3)) .
4. The final answer is routed to Load 3 of Zone A (figure 4.10 (4) and (5)).
5. Finally all loads of zone A and B are restored after the Inter-zone negotiation phase.

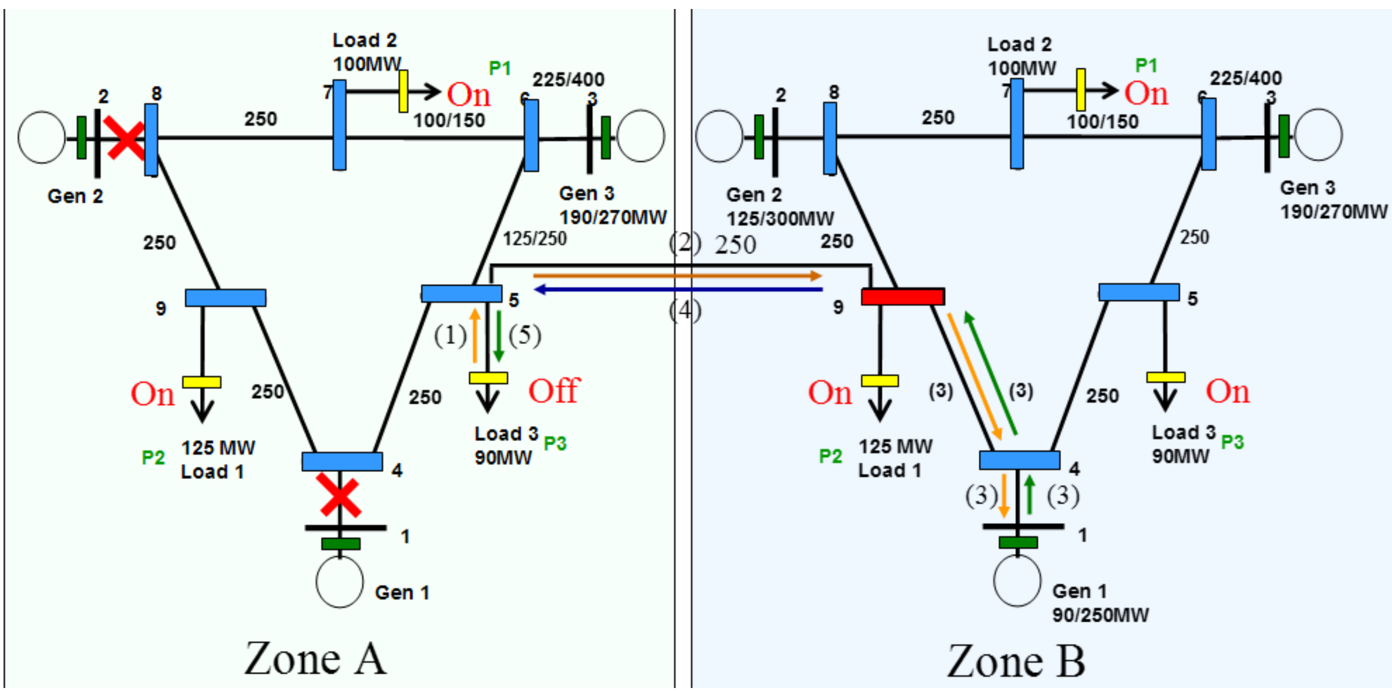


Figure 4.10: Example of Inter-zone Negotiation. Negotiation process

4.4 IPRs Messages types

Some message types were defined for IPRs communications and interactions. These message types permit a distributed control and coordination of the IPRs Network. Their mission is to maintain each IPR aware of the conditions in its neighboring IPRs . These message types are organized in two groups:

4.4.1 Normal state messages

These message types are designed to exchange information between adjacent IPRs while the EEDN is in normal state operation (steady state):

- Connection message: they contain information about each link connected to one IPR. These messages allow the IPRs to establish communication channels with others IPRs.
- Status Request: these messages are sent by a given IPR to ask another IPR for its status.
- Status Response: this message type corresponds to a message sent by an IPR when it receives a Status Request, and it contains information about operational variables of the given IPR.

4.4.2 Contingency messages

When a System failure occurs in the EEDN, these message types will be exchanged between IPRs during the system restoration process.

4.4.2.1 Intra-zone messages

These message types are designed to exchange information between IPRs to perform the system restoration in Intra-zone level.

- **Friendly stage messages:** As we presented in section 4.3.1 the first step of IPRs negotiation occurs in the friendly stage. These messages are designed to perform the first negotiation stage.
  - Get message: They are sent by loads to request more power.
  - Put response: are positive responses of an IPR to a power request received from a particular output line.
  - Deny response: are negative responses given by an IPR when it receives a request that it cannot satisfy.
- **Persistent and load shedding messages:** the second step of IPRs negotiation occurs in Persistent and load shedding stage. These messages are designed to perform the second negotiation stage.
  - Persistent Request message: They are sent by loads to request more power. These messages allow IPRs to change output lines to input lines.
  - Disconnect message: These messages are sent by Principal Power Routers or Source Generators to lower-priority loads when they receive a high-priority request and load shedding is necessary to satisfy that request.
  - Disconnect confirmation message: The loads that receive the disconnect message sends a these message type to de-allocate the resources associated to them.
  - Mandatory Get message: These messages are sent by Sink Power Routers when the load cannot served in the friendly stage. These messages allow IPRs to disconnect low-priority loads if it is necessary to supply a high-priority request.
  - Mandatory Change message: These messages are sent by Principal Power Routers to de-allocate resources of low-priority loads and allocate them to supply a high-priority request.
  - Mandatory confirmation message: When a Principal Power Routers changes resources of low-priority request to a high-priority request, it sends this message to the Principal Power Router that sent the Mandatory Change Message.

4.4.2.2 Inter-zone messages

These message types are designed to exchange information between IPRs to perform the system restoration in Inter-zone level when in Intra-zone level the IPRs cannot restore every load.

- Inter-zone Request: These messages are sent by loads when they are not served during Intra-zone negotiation level. These messages are routed across zones until they reach a border Power Router.
- Inter-zone Get message: These message are sent by a Border Power Router to it neighbor zone. When a Border Power Router receives this type of message begins an Intra-zone negotiation to supply the request.
- Inter-zone Put Message: are positive responses for an Inter-zone Get Message.
- Inter-zone Deny Message: are negative responses for an Inter-zone Get Message.

CHAPTER 5

Experimental Results

5.1 Introduction

To validate our ideas, we have implemented a software library with all the protocols and communications for IPRs operations and the algorithm presented in chapters 3 and 4. We then constructed a computer simulation, to experiment with the concepts associated with the IPRs.

The objective of our simulations consists in obtaining a reservation and allocation of power resources to enable a system restoration using new IPRs approach after a total system blackout. Thus, the IPRs will negotiate to find out an effective (but perhaps sub-optimal) allocation of power to each line and loads. The important issue here is demonstrate the capacity of IPRs to solve the restoration problem using a decentralized framework.

In order to demonstrate the effectiveness of the proposed approach many test cases were used, all using the standard test-bed systems of nine and 179-bus model of the Western Systems Coordinating Council - WSCC[1]. We present several of these simulation cases, these

[1] Western Systems Coordinating Council (WSCC) was formed with the signing of the WSCC Agreement

scenarios are organized in two groups, Intra-zone scenarios and Inter-zone scenarios. The first group is for demonstration of the effectiveness of Intra-zone negotiation scheme; and the second group is for demonstration of the effectiveness of the multi-stage negotiation scheme. Notice that we run several simulations for each scenarios, because the order in which the messages are sent and routed by IPRs varies through the time producing different allocations of the resources.

The software library was built using the Java programming language, and it was run on several computers interconnected via a 100Mbps LAN. In the early stage of this research, we used one computer for each IPR, but when we used WSCC-179 bus model, we ran the simulation using a computer for each zone. Each of these computers has a processor Pentium IV of 2.4 GHz and 512MB or 1GB in RAM.

Finally, to simplify the figures presented in this chapter, the Principal Power Router (PPR) has the Id of its Bus (e.g. For Bus 1 its PPR is PPR 1). Sink Power Router (SnkPR) has the Id of its Load (e.g. for Load 1 its SnkPR is SnkPR 1). And, each Source Power Router (ScrPR) has the Id of its Generator (e.g. for Generator 1 its SrcPR is SrcRPR 1).

5.1.1 Prototype overview

We developed a prototype that implements the IPRs concept described in this thesis. This prototype is divided into three independent software applications, but all applications have similar structure and communication scheme. Their differences are associated with their functional roles:

- **Source Power Routers:** this application implements the concepts associated with Sources Power Routers.

on August 14, 1967 by 40 electric power systems. Those "charter members" represented the electric power systems engaged in bulk power generation and/or transmission serving all or part of the 14 Western States and British Columbia, Canada. [19]

- **Sink Power Routers:** this application implements the concept associated with Sink Power Routers.
- **Principal Power Routers:** this application implements the concept associated with Sink Power Routers.

5.1.1.1 Prototype structure

As we presented above, all applications have similar multi-layer structure as shown in figure 5.1. Each one with functional roles clearly defined as described bellow:

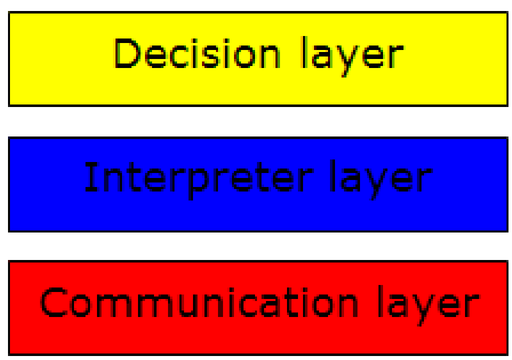


Figure 5.1: Prototype Structure

- **Communication layer.** With this layer the IPRs established the communication with others for exchanging messages. This layer uses TCP and UDP sockets to interchange messages.
- **Interpreter layer.** The messages interchanged by IPRs are built using XML. The interpreter layer receives and sends XML messages from/to the Communication layer. The interpreter layer parses these message to determine type, parameters and source, and send this information to Decision layer.
- **Decision layer.** The Decision layer is the brain of IPRs, it make decisions about routing paths, and negotiation schemes.

5.2 Intra-zone scenarios

In order to demonstrate the effectiveness of the Intra-zone negotiation algorithms, we present several scenarios where the negotiation for the system restoration occurs at the Intra-zone level. First we have four modifications of the WSCC nine-bus system, and finally we have the WSCC 179-bus system divided in five autonomous zones. These zone have the characteristic of balance between generation capacity and load demand within the zone.

5.2.1 WSCC nine-bus system - Scenario I

The goal of this simulation is to prove the effectiveness of the basic IPRs Negotiation scheme. In this case, the IPRs try to perform the system restoration after a system blackout. The model used consists of a network of three generators, six buses and three loads as depicted in figure 5.2. As we mentioned before, this is a modification of the WSCC model. In this scenario, after the blackout, every component are available for the system restoration.

Table 5.1 shows the values of the principal variables of our simulation. Each row in this table corresponds to variables associated with each bus of the system. The column "Bus" corresponds to the Identifier of the bus; the column "Line" corresponds to the identifier of each line connected to each bus; the column "Limit" corresponds to the capacity of each line in the system; the column "Reliability" corresponds to the Reliability factor associated with each line in the system and the column "Priority" corresponds to the Priority factor associated with each line in the system.

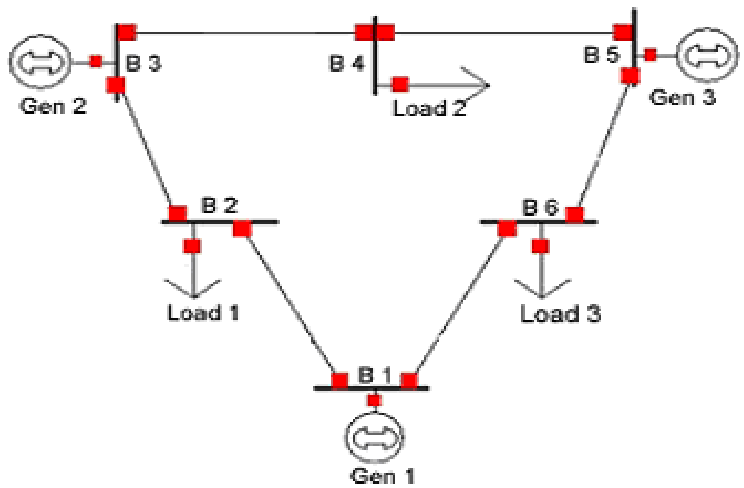


Figure 5.2: Scenario I - WSCC Nine-bus system modified

Bus	Line	Limit	Reliability	Priority
B1	Gen 1	90 MW	1	/
	B1 B2	90 MVA	/	2
	B1 B6	90 MVA	/	1
B2	B1 B2	90 MVA	2	/
	B2 B3	125 MVA	1	/
	Load 1	125 MW	/	1
B3	Gen 2	190 MW	1	/
	B2 B3	125 MVA	/	1
	B3 B4	125 MVA	/	2
B4	B3 B4	125 MVA	2	/
	B4 B5	100 MVA	1	/
	Load 2	100 MW	/	3
B5	Gen 3	100 MW	1	/
	B4 B5	100 MVA	/	1
	B5 B6	100 MVA	/	2
B6	B5 B6	100 MVA	2	/
	B1 B6	90 MVA	1	/
	Load 3	90 MW	/	2

Table 5.1: Scenario I - Simulation conditions - WSCC nine-bus system

Results of simulation

After running the test cases independent times, the power allocation negotiated by IPRs can supply 100% of the power required by loads in each case. After a total blackout, all affected SnkPRs send request messages to their high reliability suppliers. When they receive the messages request, they send a request messages to their SrcPRs. The SrcPRs verify the generators status, and reply to the request. The SrcIPRs allocate the power of their generators and send a affirmative response to IPRs that made the requests. These responses are sent across network allocating power at each line for system restoration.

The allocation of power satisfies the constraints established in the mathematical formulation (section 3.2). Moreover, this allocation of power is done in a decentralized manner, using only local information. Table 5.2 presents the allocation of power for each of the elements in the system. In this table each row corresponds to the variables associated with each bus in the system and its value after running the simulation. The three first columns correspond has the same mean in table 5.1 and the column "Output" represents the flow magnitude assigned to each line as Simulation result.

5.2.2 WSCC nine-bus system - Scenario II

The objective of this scenario is to demonstrate the capacity of Source Power Routers to make decisions for load shedding if it is needed to guarantee the service to high-priority loads. The model used consists of a network of three generators, nine buses and three loads as depicted in figure 5.3, this figure shows the Lines capacity, Generators capacity and Loads priority and demand. As we mentioned before, this is a modification of the WSCC-nine bus model. In the Scenario I the system has all resource available. But, in this Scenario the system has the lines B8-B3 and B1-B7 out of service. The generation capacity available is 270MW and the total demand is 315MW, this situation means that

Bus	Line	Limit	Output
B1	Gen 1	90 MW	90 MW
	B1 B2	90 MVA	0 MW
	B1 B6	90 MVA	90 MW
B2	B1 B2	90 MVA	0 MW
	B2 B3	125 MVA	125 MW
	Load 1	125 MW	125 MW
B3	Gen 2	190 MW	125 MW
	B2 B3	125 MVA	125 MW
	B3 B4	125 MVA	0 MW
B4	B3 B4	125 MVA	0 MW
	B4 B5	100 MVA	100 MW
	Load 2	100 MW	100 MW
B5	Gen 3	100 MW	100 MW
	B4 B5	100 MVA	100 MW
	B5 B6	100 MVA	0 MW
B6	B5 B6	100 MVA	0 MW
	B1 B6	90 MVA	90 MW
	Load 3	90 MW	90 MW

Table 5.2: Scenario I - Simulation results - WSCC nine-bus system

some loads must remain un-served after the negotiation process.

Results of simulation

After running the test cases ten different times, in all cases the power allocation negotiated by IPRs can supply higher priority loads (load 1 and load 2). The negotiation process is performed in this way: After the friendly stage, loads 2 and 3 are served but Load 1 is disconnected. Because, Load 3 (priority 3) has lower priority than load 1 (priority 2) the system use Persistent Stage to allocate power for load 1; Sink Power Router (SnkPR 1) sends a Persistent Get Message, this message is routed until it reaches Source Power Router (SrcPR 3) connected to Generator 3. This SrcPR 3 make decision to disconnect lowest priority load (load 3) because the limit of the generator only let it to supply load 1 if it disconnects the load 3. The disconnect message is send to Sink Power Router 3 (SnkPR 3) and the put message is routed from SrcPR3 to SnkPR 1 to supply load 1. Finally, loads 1

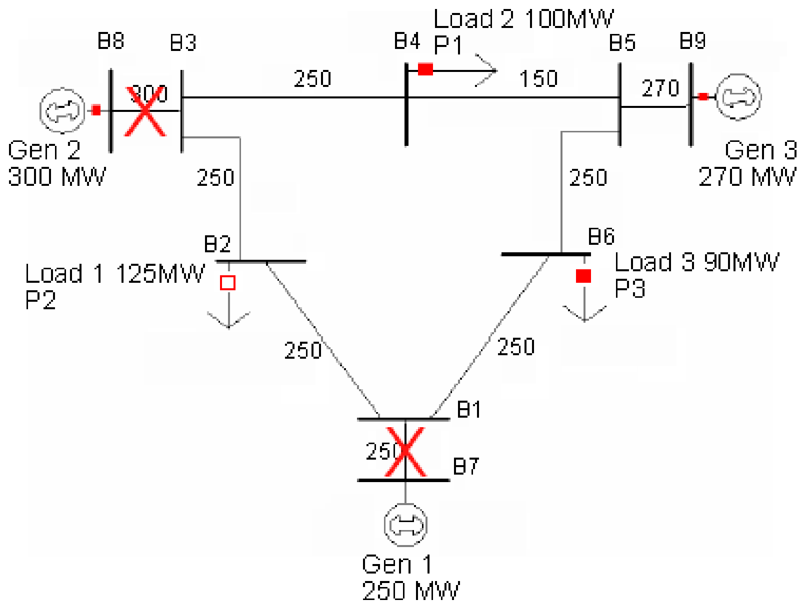


Figure 5.3: Scenario II - WSCC nine-bus system

and 2 with high-priorities are served while the lowest-priority load (load 3) is disconnected.

The allocation of power satisfies the constraints established in the mathematical formulation (section 3.2). Moreover, this allocation of power is done in de-centralized manner, using only local information. Table 5.3 presents the allocation of power for each load in the system in friendly and persistent stage. Table 5.4 presents power allocation in each generator of the system after friendly and persistent stages. And, table 5.5 shows the values of the principal variables on buses and lines of our simulations such as capacity (Limit column), Availability(status column), power allocated after Friendly Stage(Friendly Stage column) and power allocated after Persistent stage(Persistent Stage column).

Load	Priority	Value	Initial status	Friendly stage	Persistent Stage
Load 1	2	125	Un-served	Un-served	Served
Load 2	1	100	Un-served	Served	Served
Load 3	3	90	Un-served	Served	Un-served

Table 5.3: Scenario II - Loads status - WSCC nine-bus system

Generator	Line	Limit	Status	Friendly stage	Persistent Stage
Gen 1	B7 - Gen 1	250	Available	0	0
Gen 2	B8 - Gen 2	300	Available	0	0
Gen 3	B9 - Gen 3	270	Available	190	225

Table 5.4: Scenario II - Generators status - WSCC nine-bus system

Bus	Line	Limit	Status	Friendly Stage	Persistent Stage
B1	B1 - B7	250	un-Available	0	0
	B1 B2	250	Available	0	0
	B1 B6	250	Available	0	125
B2	B1 B2	250	Available	0	0
	B2 B3	250	Available	0	125
	B2 - Load 1	125	Available	0	125
B3	B3 - B8	300	un-Available	0	0
	B2 B3	250	Available	0	0
	B3 B4	250	Available	0	0
B4	B3 B4	250	Available	0	0
	B4 B5	150	Available	100	100
	B4 - Load 2	100	Available	100	100
B5	B5 - B9	400	Available	190	225
	B4 B5	150	Available	100	100
	B5 B6	250	Available	90	125
B6	B5 B6	250	Available	90	125
	B1 B6	250	Available	0	125
	B6 - Load 3	90	Available	90	0
B7	B1 - B7	250	un-Available	0	0
	B7 - Gen 1	250	Available	0	0
B8	B2 - B8	300	un-Available	0	0
	B8 - Gen 2	300	Available	0	0
B9	B5 - B9	400	Available	190	225
	B9 - Gen 3	270	Available	190	225

Table 5.5: Scenario II - Bus and lines status - WSCC nine-bus system

5.2.3 WSCC nine-bus system - Scenario III

The objective of this scenario is to demonstrate the capacity of Principal Power Routers to make decisions for load shedding if it is needed to guarantee the service to higher-priority loads. The model used consists of a network of three generators, nine buses and three loads as depicted in figure 5.4. As we mentioned before, this is a modification of the WSCC model. In this Scenario, like Scenario II, the system has the lines B8-B3 and B1-B7 out-of-service. In scenario II the load shedding is performed from Source Power Routers because the limitation of the system is given by the generation capacity. In this Scenario the limitation is given by line B5-B9 that does not support all amount of power flow requested by the loads.

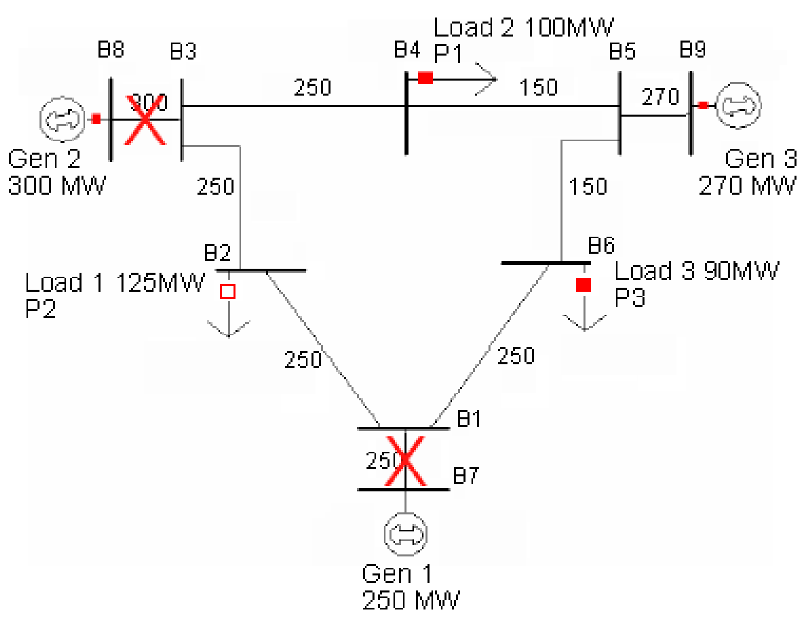


Figure 5.4: Scenario III - WSCC nine-bus system

Results of simulation

After running the test cases ten different times, in all cases the power allocation negotiated by IPRs can supply higher priority loads (load 1 and load 2). The negotiation process is performed in as follow:

After friendly stage loads 2 and 3 are served while load 1 is disconnected. But, load 3 (priority 3) has lower priority than load 1 (priority 2). Then the system use Persistent Stage to allocate power for load 1; Sink Power Router (SnkPR 1) sends a Persistent Get Message (PGM). Principal Power Router 6 (PPR 6) get the message and make decision to disconnect lowest priority load (load 3) because the limit of its input line only lets it to supply load 1 if it disconnects the load 3. The disconnect message is send to Sink Power Router 3 (SnkPR 3) and PPR 6 make a Mandatory Change Message (MCHM) to assign the resource allocated for load 3 to load 1, and this MCHM is routed until it reaches Source Power Router (SrcPR 3) connected to Generator 3. SrcPR 3 assign the resources needed to supply load 1, and sends the final response to PPR 6. PPR 6 gets the response and sends a put message to SnkPR 1. Finally, loads 1 and 2 with high-priorities are served while the lowest-priority load (load 3) are un-served.

The allocation of power satisfies the constraints established in the mathematical formulation (section 3.2). Moreover, this allocation of power is done in de-centralized manner, using only local information. Table 5.6 presents the allocation of power for each load in the system in friendly and persistent stage. Table 5.7 presents power allocation in each generator of the system after friendly and persistent stage. And, table 5.8 shows the values of the principal variables on buses and lines of our simulations such as capacity (Limit column), Availability(status column), power allocated after Friendly Stage(Friendly Stage column) and power allocated after Persistent Stage(Persistent Stage column).

Load	Priority	Value	Initial status	Friendly stage	Persistent Stage
Load 1	2	125	Un-served	Un-served	Served
Load 2	1	100	Un-served	Served	Served
Load 3	3	90	Un-served	Served	Un-served

Table 5.6: Scenario III - Loads status - WSCC nine-bus system

Generator	Line	Limit	Status	Friendly stage	Persistent Stage
Gen 1	B7 - Gen 1	250	Available	0	0
Gen 2	B8 - Gen 2	300	Available	0	0
Gen 3	B9 - Gen 3	270	Available	190	225

Table 5.7: Scenario III - Generators status - WSCC nine-bus system

Bus	Line	Limit	Status	Friendly Stage	Persistent Stage
B1	B1 - B7	250	un-Available	0	0
	B1 B2	250	Available	0	0
	B1 B6	250	Available	0	125
B2	B1 B2	250	Available	0	0
	B2 B3	250	Available	0	125
	B2 - Load 1	125	Available	0	125
B3	B3 - B8	300	un-Available	0	0
	B2 B3	250	Available	0	0
	B3 B4	250	Available	0	0
B4	B3 B4	250	Available	0	0
	B4 B5	150	Available	100	100
	B4 - Load 2	100	Available	100	100
B5	B5 - B9	250	Available	190	225
	B4 B5	150	Available	100	100
	B5 B6	150	Available	90	125
B6	B5 B6	150	Available	90	125
	B1 B6	250	Available	0	125
	B6 - Load 3	90	Available	90	0
B7	B1 - B7	250	un-Available	0	0
	B7 - Gen 1	250	Available	0	0
B8	B2 - B8	300	un-Available	0	0
	B8 - Gen 2	300	Available	0	0
B9	B5 - B9	250	Available	190	225
	B9 - Gen 3	270	Available	190	225

Table 5.8: Scenario III - Bus and lines status - WSCC nine-bus system

5.2.4 WSCC nine-bus system - Scenario IV

The objective of this scenario is to demonstrate the capacity of Principal Power Routers to make split requests (section 3.6) and the capacity of Principal Routers to make decisions for load shedding if it is needed. The model used consists of a network of three generators, nine buses and three loads as depicted in figure 5.5. In this Scenario, like Scenario II, the system has the lines B8-B3 and B1-B7 out-of-service. As we mentioned before, this is a modification of the WSCC-nine bus model.

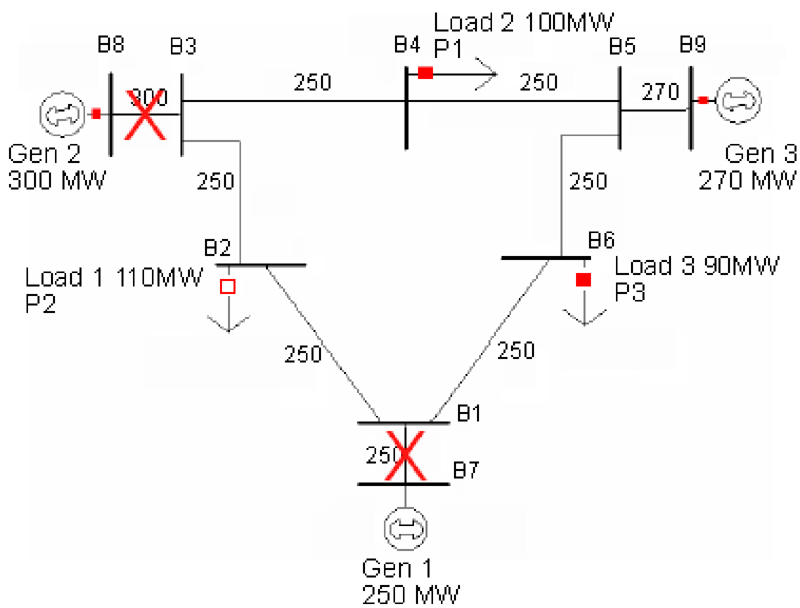


Figure 5.5: Scenario IV - WSCC nine-bus system

Results of simulation

After running the test cases ten different times, in all cases the power allocation negotiated by IPRs can supply higher priority loads (load 1 and load 2). After friendly stage loads 2 and 3 are served but load 3 (priority 3) is low-priority than load 1 (priority 2).

Then the system use Persistent Stage to allocate power for load 1; Principal Power Router in bus 2 (PPR 2), with the information obtained from Friendly stage, makes decision to send split request across lines B2-B1 and B2-B3. These requests are routed until they reach PPR 5, PPR 5 check the capacity of its input line and makes the decision of disconnect load 3 (with less priority than load 1). The resources are allocated to supply load 1 and the response is routed to load 1. Finally, loads 1 and 2 with high-priorities are served while the lowest-priority load (load 3) is un-served.

The allocation of power satisfies the constraints established in the mathematical formulation (section 3.2). Moreover, this allocation of power is done in de-centralized manner, using only local information. Table 5.9 presents the allocation of power for each load in the system in friendly and persistent stage. Table 5.10 presents power allocation in each generator of the system after friendly and persistent stage. And, table 5.11 shows the values of the principal variables on buses and lines of our simulations such as capacity (Limit column), Availability(status column), power allocated after Friendly Stage(Friendly Stage column) and power allocated after Persistent Stage(Persistent Stage column).

Load	Priority	Value	Initial status	Friendly stage	Persistent Stage
Load 1	2	110	Un-served	Un-served	Served
Load 2	1	100	Un-served	Served	Served
Load 3	3	90	Un-served	Served	Un-served

Table 5.9: Scenario IV - Loads status - WSCC nine-bus system

Generator	Line	Limit	Status	Friendly stage	Persistent Stage
Gen 1	B7 - Gen 1	250	Available	0	0
Gen 2	B8 - Gen 2	300	Available	0	0
Gen 3	B9 - Gen 3	270	Available	190	210

Table 5.10: Scenario IV - Generators status - WSCC nine-bus system

Bus	Line	Limit	Status	Friendly Stage	Persistent Stage
B1	B1 - B7	250	un-Available	0	0
	B1 B2	250	Available	0	0
	B1 B6	250	Available	0	110
B2	B1 B2	250	Available	0	0
	B2 B3	250	Available	0	110
	B2 - Load 1	110	Available	0	110
B3	B3 - B8	300	un-Available	0	0
	B2 B3	250	Available	0	0
	B3 B4	250	Available	0	0
B4	B3 B4	250	Available	0	0
	B4 B5	150	Available	100	100
	B4 - Load 2	100	Available	100	100
B5	B5 - B9	270	Available	190	210
	B4 B5	150	Available	100	100
	B5 B6	250	Available	90	110
B6	B5 B6	250	Available	90	110
	B1 B6	250	Available		110
	B6 - Load 3	90	Available	90	0
B7	B1 - B7	250	un-Available	0	0
	B7 - Gen 1	250	Available	0	0
B8	B2 - B8	300	un-Available	0	0
	B8 - Gen 2	300	Available	0	0
B9	B5 - B9	270	Available	190	210
	B9 - Gen 3	270	Available	190	210

Table 5.11: Scenario IV - Bus and lines status - WSCC nine-bus system

5.2.5 WSCC nine-bus system - Scenario V

The objective of this scenario is to demonstrate the capacity of Principal Power Routers to make split requests without load shedding. The model used consists of a network of three generators, nine buses and three loads as depicted in figure 5.6. As we mentioned before, this is a modification of the WSCC model. In this Scenario, like Scenario II, the system has the lines B8-B3 and B1-B7 out-of-service. Table 5.14 shows the values of the principal variables on buses and lines of our simulations.

Results of simulation

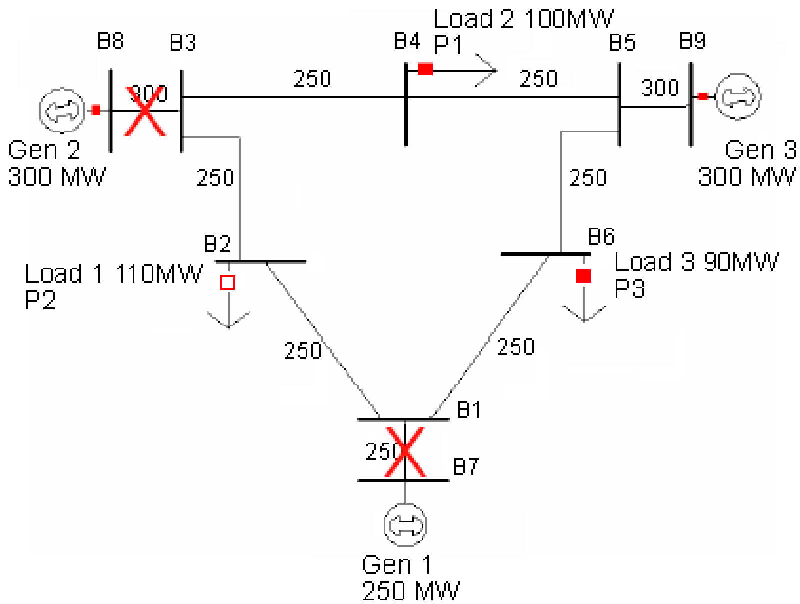


Figure 5.6: Scenario V - WSCC nine-bus system

After running the test cases ten times, in all cases the power allocation negotiated by IPRs can supply all loads (load 1, load 2 and load 3). After friendly stage loads 2 and 3 are served but load 3 (priority 3) is less-priority than load 1 (priority 2). Then the system use Persistent Stage to allocate power for load 1. Principal Power Routed in bus 2 (PPR 2), with the information obtained from Friendly stage, makes decision to send split request across lines B2-B1 and B2-B3. These requests are routed until they reach PPR 5, PPR 5 checks the capacity of its input line and routes the requests to SrcPR 3. The resources are allocated to supply load 1 and the response are routed to load 1. Finally, loads 1, 2 and 3 are served.

The allocation of power satisfies the constraints established in the mathematical formulation (section 3.2). Moreover, this allocation of power is done in de-centralized manner, using only local information. Table 5.12 presents the allocation of power for each load in the system in friendly and persistent stage. Table 5.13 presents power allocation in each generator of the system after friendly and persistent stage. And, table 5.14 shows the values of the principal variables on buses and lines of our simulations such as capacity (Limit column), Availability(status column), power allocated after Friendly Stage(Friendly Stage column) and power allocated after Persistent Stage(Persistent Stage column).

Load	Priority	Value	Initial status	Friendly stage	Persistent Stage
Load 1	2	110	Un-served	Un-served	Served
Load 2	1	100	Un-served	Served	Served
Load 3	3	90	Un-served	Served	Served

Table 5.12: Scenario V - Loads status - WSCC nine-bus system

Generator	Line	Limit	Status	Friendly stage	Persistent Stage
Gen 1	B7 - Gen 1	250	Available	0	0
Gen 2	B8 - Gen 2	300	Available	0	0
Gen 3	B9 - Gen 3	300	Available	190	300

Table 5.13: Scenario V - Generators status - WSCC nine-bus system

Bus	Line	Limit	Status	Friendly Stage	Persistent Stage
B1	B1 - B7	250	un-Available	0	0
	B1 B2	250	Available	0	60
	B1 B6	250	Available	0	60
B2	B1 B2	250	Available	0	60
	B2 B3	250	Available	0	50
	B2 - Load 1	110	Available	0	110
B3	B3 - B8	300	un-Available	0	0
	B2 B3	250	Available	0	50
	B3 B4	250	Available	0	50
B4	B3 B4	150	Available	0	50
	B4 B5	150	Available	100	150
	B4 - Load 2	100	Available	100	100
B5	B5 - B9	300	Available	190	300
	B4 B5	150	Available	100	150
	B5 B6	150	Available	90	150
B6	B5 B6	150	Available	90	150
	B1 B6	250	Available	0	60
	B6 - Load 3	90	Available	90	90
B7	B1 - B7	250	un-Available	0	0
	B7 - Gen 1	250	Available	0	0
B8	B2 - B8	300	un-Available	0	0
	B8 - Gen 2	300	Available	0	0
B9	B5 - B9	300	Available	190	300
	B9 - Gen 3	300	Available	190	300

Table 5.14: Scenario V - Bus and lines status - WSCC nine-bus system

5.2.6 WSCC 179-bus System

The model used consists of a network of 29 generators, 179 buses and 113 loads. The system is divided into five zones (1-A, 1-B, 1-B, 2-A and 2-B) as depicted in figure 5.7. In the original model several loads are network equivalents with a negative value, this means that in these section the generation exceeds the demand. For our simulation these loads with negative loads are generators. Then the number of generator increase while the number of loads decrease.

The objective of this scenario is to restore the system after a total blackout. We worked with less Principal Power Routers than buses in the system because a PPR could manage one or more buses. In this model the buses PPRs are located at the buses that have at least three lines. Because, in buses with two lines the IPR do not need to choice which line the will serve.

Figure 5.8, 5.9, 5.10, 5.11 and 5.12 show the schemes of Zone 1-A, 1-B, 1-C, 2-A and 2-B respectively.

Results of simulation

After running separately several simulations for each zone, we obtain that in zones 1-A, 1-B,1-C and 2A the IPR network could allocate resources every time to supply all loads. But in Zone 2-B the IPR network could allocate resources for 84% of loads in the best case and 76% of loads in the worse case but **every high-priority loads** were supplied in this zone. Tables 5.15 to 5.24 show the results of negotiation in each zone of WSCC 179-bus system in one of simulation performed. The power allocated in each generator is not the same always, but in all simulations performed the power generated match with the power demand by loads in each zone.

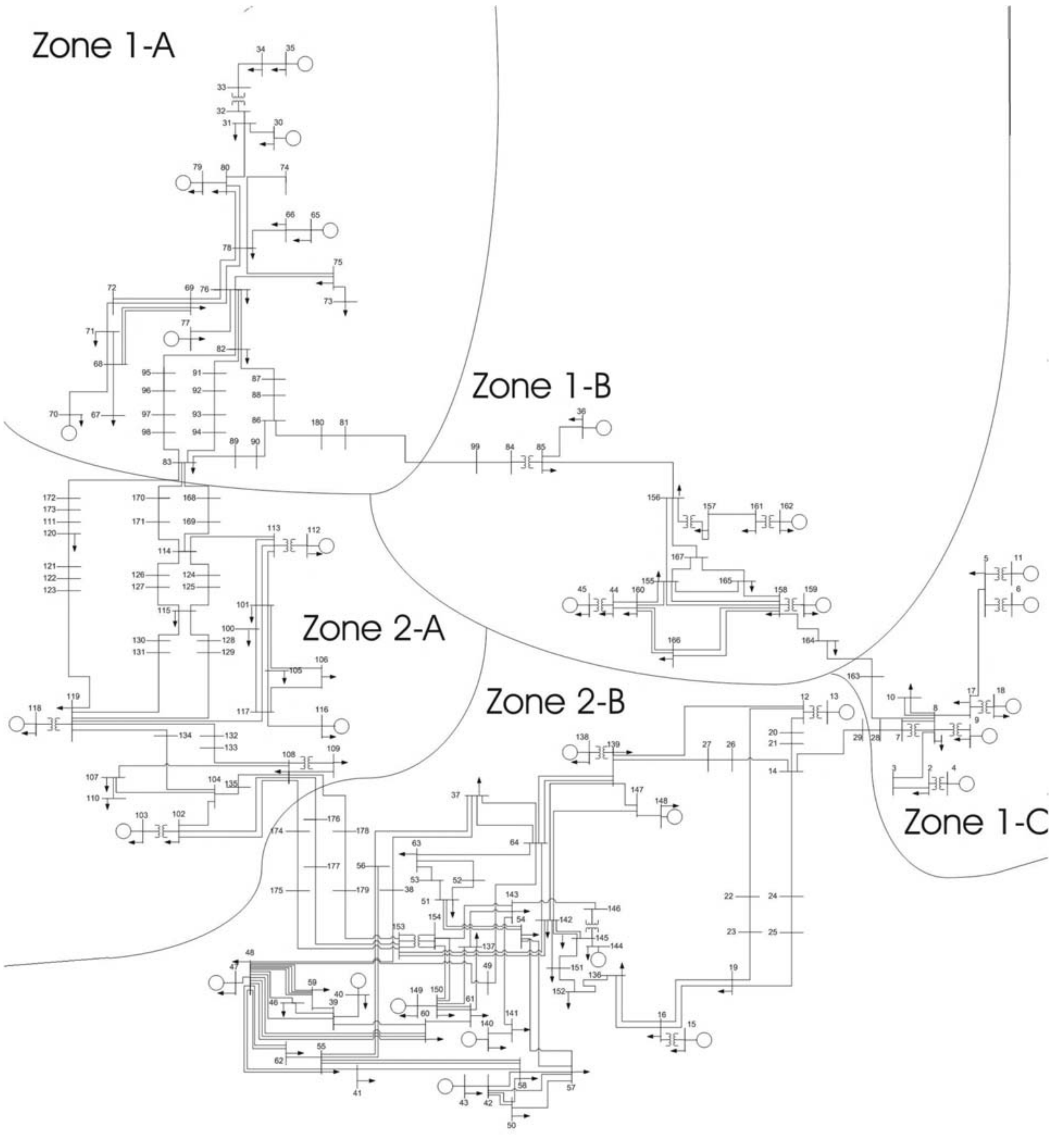


Figure 5.7: WSCC 179-bus model

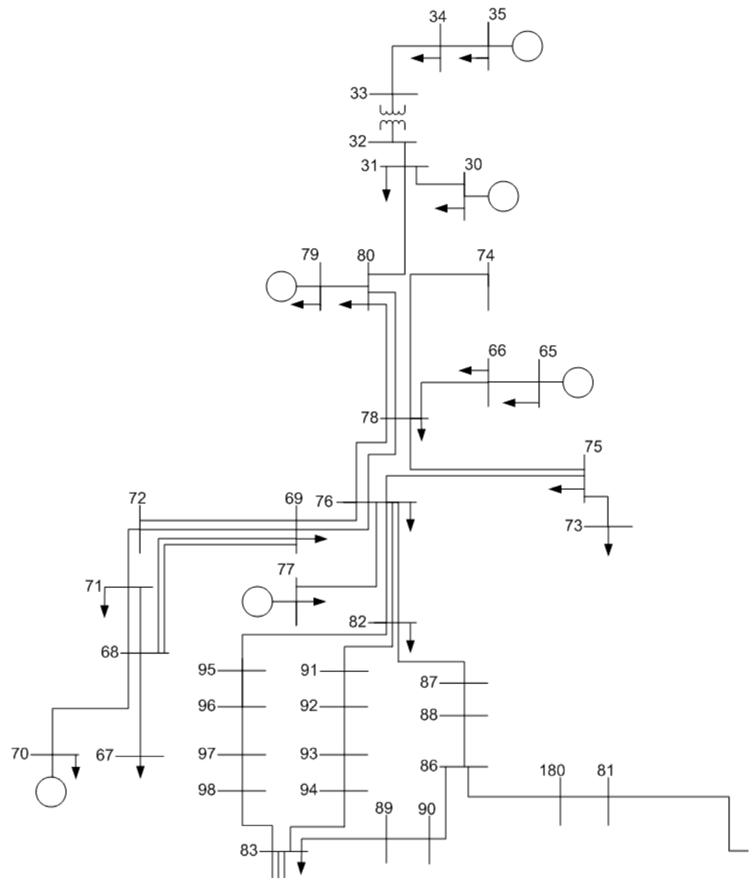


Figure 5.8: WSCC 179-bus model - Zone 1-A

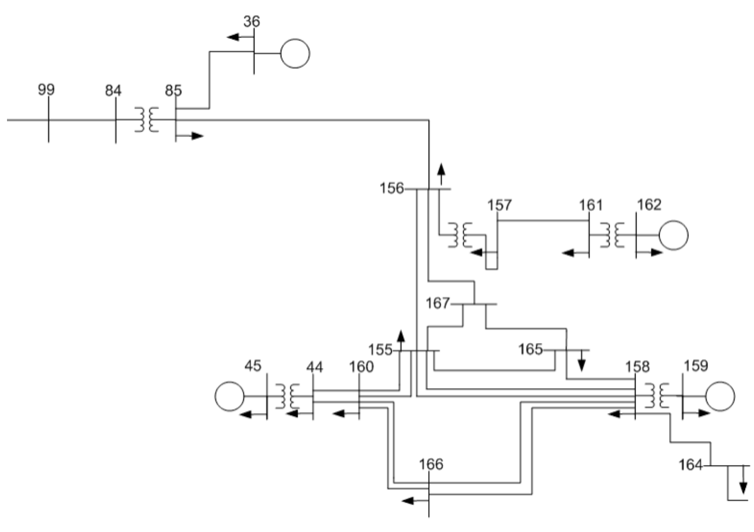


Figure 5.9: WSCC 179-bus model - Zone 1-B

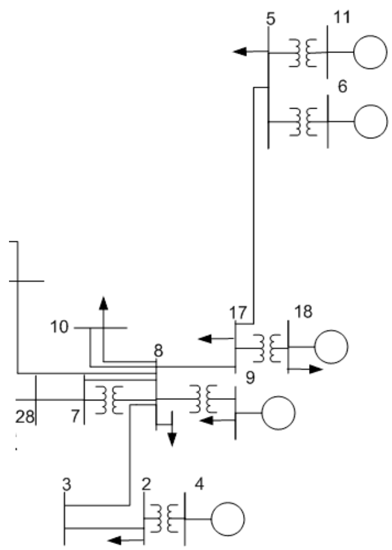


Figure 5.10: WSCC 179-bus model - Zone 1-C

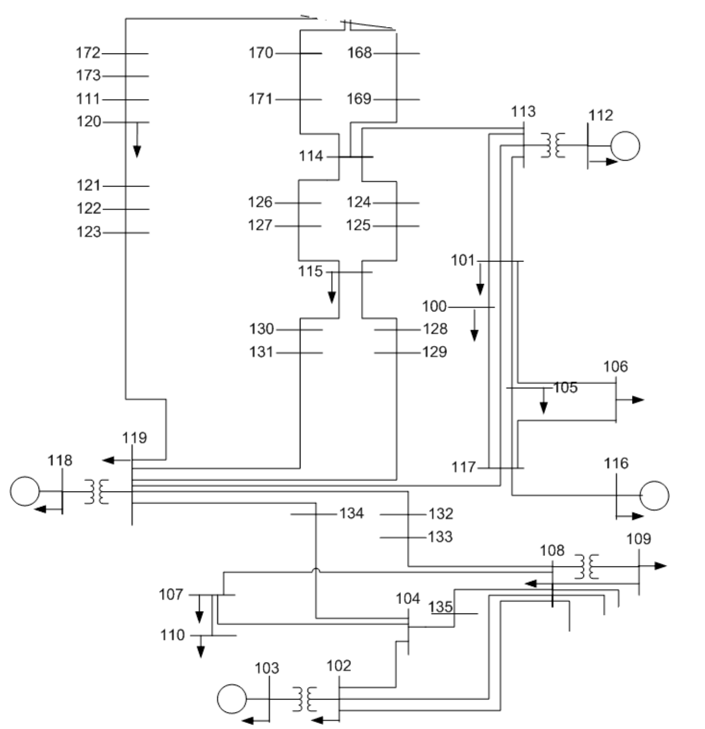


Figure 5.11: WSCC 179-bus model - Zone 2-A

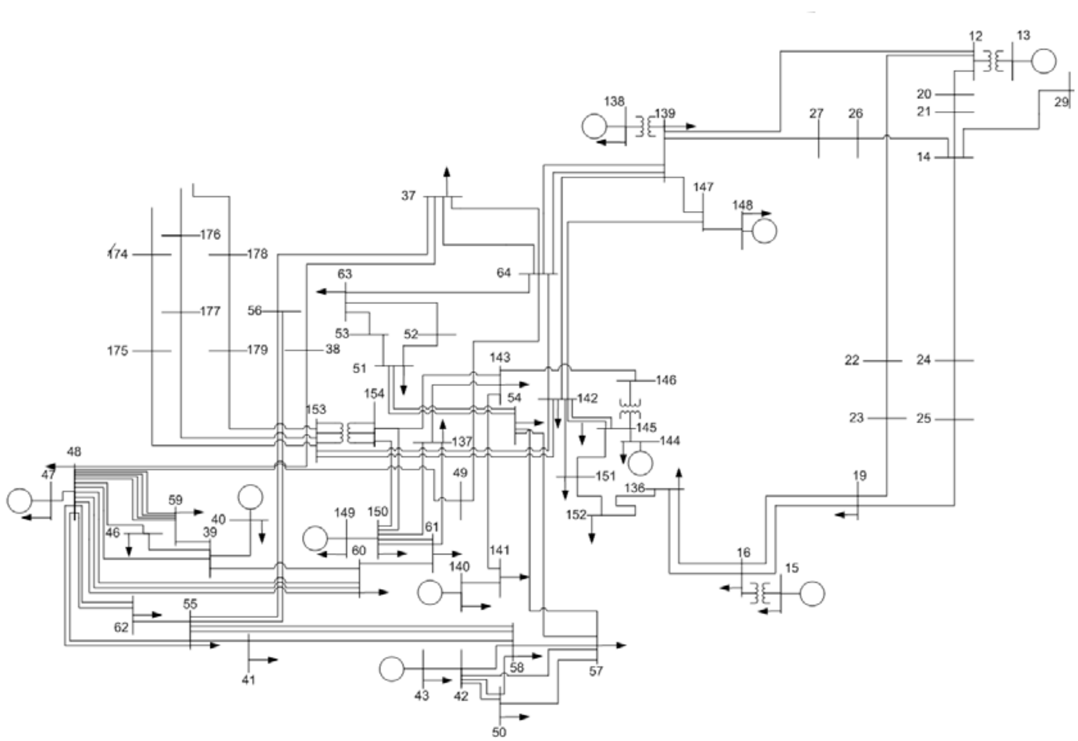


Figure 5.12: WSCC 179-bus model - Zone 2-B

The allocation of power satisfies the constraints established in the mathematical formulation (section 3.2). Moreover, this allocation of power is done in de-centralized manner, using only local information.

Results of simulation - Zone 1-A

In this zone the IPRs negotiation gets to supply all loads with the internal generation capacity in every simulation. The resources allocation change in each simulation. Table 5.15 presents the Power Allocation for each generators in this zone. The column "Generator" corresponds to the bus where the generator is connected. The column "Line" corresponds the Identifier of the line between the Generator and its bus. The column "Limit" corresponds to the Generator Capacity, Column "Status" corresponds to Generator Availability and Column "Final" corresponds to Power Allocation for each generator.

The Table 5.16 presents the status of each Load in this zone during the negotiation process. The column "Load" corresponds to the bus where the load is connected. The column "Priority" corresponds to the Load Priority. The column "Initial Status" corresponds the Initial status after the blackout and Columns "Friendly stage" and "Persistent Stage" correspond to the Load status after each negotiation stage respectively.

Generator	Line	Limit	Status	Final
Gen 30	B 30 - Gen 30	10000	Available	4500
Gen 35	B 35 - Gen 35	10000	Available	3700
Gen 65	B 65 - Gen 65	10000	Available	5232
Gen 68	B 68 - Gen 68	67.5	Available	0
Gen 69	B 69 - Gen 69	44.2	Available	0
Gen 70	B 70 - Gen 70	10000	Available	972
Gen 73	B 73 - Gen 73	1525	Available	0
Gen 77	B 77 - Gen 77	10000	Available	4877
Gen 79	B 79 - Gen 79	10000	Available	8600
Gen 82	B 82 - Gen 82	66.6	Available	0
Gen 83	B 83 - Gen 83	339	Available	0
Total Generated				27881

Table 5.15: WSCC 179-bus system - Zone 1-A - Generators status

Load	Priority	Value	Initial status	Friendly stage	Persistent Stage
30	2	100	Un-served	Served	Served
31	3	4400	Un-served	Served	Served
34	2	3600	Un-served	Served	Served
35	3	100	Un-served	Served	Served
65	3	100	Un-served	Served	Served
66	3	1700	Un-served	Served	Served
67	3	160	Un-served	Un-served	Served
70	3	100	Un-served	Served	Served
71	3	3137	Un-served	Un-served	Served
75	3	2584	Un-served	Un-served	Served
76	3	3200	Un-served	Served	Served
77	3	100	Un-served	Served	Served
78	1	3500	Un-served	Un-served	Served
79	2	100	Un-served	Served	Served
80	2	5000	Un-served	Served	Served
Total Loads		27881		66.35%	100%

Table 5.16: WSCC 179-bus system - Zone 1-A - Loads status

Results of simulation - Zone 1-B

In this zone the IPRs negotiation gets to supply for all loads with the internal generation capacity in every simulation. The resources allocation change in each simulation. Table 5.17 presents the Power Allocation for each generators in this zone. The column "Generator" corresponds to the bus where the generator is connected. The column "Line" corresponds the Identifier of the line between the Generator and its bus. The column "Limit" corresponds to the Generator Capacity, Column "Status" corresponds to Generator Availability and Column "Final" corresponds to Power Allocation for each generator.

The Table 5.18 presents the status of each Load in this zone during the negotiation process. The column "Load" corresponds to the bus where the load is connected. The column "Priority" corresponds to the Load Priority. The column "Initial Status" corresponds the Initial status after the blackout and Columns "Friendly stage" and "Persistent Stage" correspond to the Load status after each negotiation stage respectively.

Generator	Line	Limit	Status	Final
Gen 36	B 36 - Gen 36	10000	Available	891.9
Gen 45	B 45 - Gen 45	10000	Available	2153
Gen 159	B 159 - Gen 159	10000	Available	1410.6
Gen 160	B 160 - Gen 160	62	Available	
Gen 162	B 162 - Gen 162	10000	Available	355
Total Generated				4810.5

Table 5.17: WSCC 179-bus system - Zone 1-B - Generators status

Load	Priority	Value	Initial status	Friendly stage	Persistent Stage
36	2	100	un-served	served	served
44	1	2053	un-served	served	served
45	3	100	un-served	served	served
85	1	610	un-served	served	served
155	3	457.7	un-served	served	served
156	3	33.9	un-served	served	served
157	3	148	un-served	served	served
158	3	116.1	un-served	served	served
159	1	100	un-served	served	served
161	2	255	un-served	served	served
162	3	100	un-served	served	served
164	1	31.6	un-served	served	served
165	2	141.2	un-served	served	served
166	3	379	un-served	served	served
167	2	185	un-served	served	served
Total Loads		4810.5		100%	100%

Table 5.18: WSCC 179-bus system - Zone 1-B - Loads status

Results of simulation - Zone 1-C

In this zone the IPRs negotiation gets to supply for all loads with the internal generation capacity in every simulation. The resources allocation change in each simulation. Table 5.19 presents the Power Allocation for each generators in this zone. The column "Generator" corresponds to the bus where the generator is connected. The column "Line" corresponds the Identifier of the line between the Generator and its bus. The column "Limit" corresponds to the Generator Capacity, Column "Status" corresponds to Generator Availability and Column "Final" corresponds to Power Allocation for each generator.

The Table 5.20 presents the status of each Load in this zone during the negotiation process. The column "Load" corresponds to the bus where the load is connected. The column "Priority" corresponds to the Load Priority. The column "Initial Status" corresponds the Initial status after the blackout and Columns "Friendly stage" and "Persistent Stage" correspond to the Load status after each negotiation stage respectively.

Generator	Line	Limit	Status	Final
Gen 9	B 9 - Gen 9	10000	Available	2228.7
Gen 4	B 4 - Gen 4	10000	Available	100
Gen 6	B 6 - Gen 6	10000	Available	2060
Gen 11	B 11 - Gen 11	10000	Available	1330
Gen 18	B 18 - Gen 18	10000	Available	100
Total Generated				5818.7

Table 5.19: WSCC 179-bus system - Zone 1-C - Generators status

Load	Priority	Value	Initial status	Friendly stage	Persistent Stage
2	3	1750	un-served	served	served
4	3	100	un-served	served	served
5	3	2350	un-served	served	served
6	2	100	un-served	served	served
8	2	239	un-served	served	served
9	3	100	un-served	served	served
10	2	139.7	un-served	served	served
11	1	100	un-served	served	served
17	3	840	un-served	served	served
18	2	100	un-served	served	served
Total Loads		5818.7		100%	100%

Table 5.20: WSCC 179-bus system - Zone 1-C - Loads status

Results of simulation - Zone 2-A

In this zone the IPRs negotiation gets to supply for all loads with the internal generation capacity in every simulation. The resources allocation change in each simulation. Table 5.21 presents the Power Allocation for each generators in this zone. The column "Generator" corresponds to the bus where the generator is connected. The column "Line" corresponds the Identifier of the line between the Generator and its bus. The column "Limit" corresponds to the Generator Capacity, Column "Status" corresponds to Generator Availability and Column "Final" corresponds to Power Allocation for each generator.

The Table 5.22 presents the status of each Load in this zone during the negotiation process. The column "Load" corresponds to the bus where the load is connected. The column "Priority" corresponds to the Load Priority. The column "Initial Status" corresponds the Initial status after the blackout and Columns "Friendly stage" and "Persistent Stage" correspond to the Load status after each negotiation stage respectively.

Generator	Line	Limit	Status	Persistant Stage
100	B 100 - 100	43.3	Available	0
103	B 103 - 103	10000	Available	815.6
111	B 111 - 111	189	Available	0
112	B 112 - 112	10000	Available	493.91
115	B 115 - 115	0.7	Available	0
116	B 116 - 116	10000	Available	984
118	B 118 - 118	10000	Available	6538.6
Total Generated				8832.11

Table 5.21: WSCC 179-bus system - Zone 2-A - Generators status

Load	Priority	Value	Initial status	Friendly stage	Persistent Stage
101	1	210.4	un-served	served	served
102	3	50	un-served	served	served
103	1	100	un-served	served	served
104	2	305	un-served	served	served
105	2	27.5	un-served	served	served
106	2	8.01	un-served	served	served
107	1	265	un-served	served	served
108	2	55.6	un-served	served	served
109	1	777.6	un-served	served	served
110	3	40	un-served	served	served
112	3	100	un-served	served	served
113	2	148	un-served	served	served
116	3	100	un-served	served	served
117	3	884	un-served	served	served
118	3	100	un-served	served	served
119	3	5661	un-served	un-served	served
Total Loads		8832.11		35.9%	100%

Table 5.22: WSCC 179-bus system - Zone 2-A - Loads status

Results of simulation - Zone 2-B

In this zone the IPR network could allocate resources for 84% of loads in the best case and 76% of loads in the worse case. But in every simulation, **every high-priority loads** are supplied in this zone with the internal generation capacity of this zone. The resources allocation change in each simulation. Table 5.23 presents the Power Allocation for each generators in this zone. The column "Generator" corresponds to the bus where the generator is connected. The column "Line" corresponds the Identifier of the line between the Generator and its bus. The column "Limit" corresponds to the Generator Capacity, Column "Status" corresponds to Generator Availability and Column "Final" corresponds to Power Allocation for each generator.

The Table 5.24 presents the status of each Load in this zone during the negotiation process. The column "Load" corresponds to the bus where the load is connected. The column "Priority" corresponds to the Load Priority. The column "Initial Status" corresponds the Initial status after the blackout and Columns "Friendly stage" and "Persistent Stage" correspond to the Load status after each negotiation stage respectively.

Generator	Line	Limit	Status	Final
Gen 13	B 13 - Gen 13	10000	Available	3287.2
Gen 15	B 15 - Gen 15	10000	Available	2155.4
Gen 37	B 37 - Gen 37	1862	Available	0
Gen 40	B 40 - Gen 40	10000	Available	921.6
Gen 43	B 43 - Gen 43	10000	Available	537
Gen 46	B 46 - Gen 46	72.8	Available	0
Gen 47	B 47 - Gen 47	10000	Available	1012.5
Gen 60	B 60 - Gen 60	2771	Available	0
Gen 63	B 63 - Gen 63	129	Available	0
Gen 138	B 138 - Gen 138	10000	Available	1206.5
Gen 140	B 140 - Gen 140	10000	Available	3291
Gen 144	B 144 - Gen 144	10000	Available	100
Gen 148	B 148 - Gen 148	10000	Available	1330
Gen 149	B 149 - Gen 149	10000	Available	3676
Total Generated				17517.2

Table 5.23: Generators status - WSCC 179-bus system - Zone 2-B

Load	Priority	Value	Initial status	Friendly stage	Persistent Stage
12	1	90	Un-served	served	served
13	3	100	Un-served	served	served
15	1	100	Un-served	served	served
16	3	793.4	Un-served	served	served
19	3	617	Un-served	served	served
40	3	100	Un-served	served	served
41	3	135	Un-served	un-served	served
43	3	100	Un-served	served	served
47	3	100	Un-served	served	served
48	3	121	Un-served	served	served
50	2	320	Un-served	served	served
51	3	237.2	Un-served	un-served	served
54	2	138	Un-served	un-served	served
55	3	807.8	Un-served	un-served	served
57	1	117	Un-served	served	served
58	3	121	Un-served	served	served
59	2	887.7	Un-served	un-served	served
61	1	401	Un-served	un-served	served
62	2	205.2	Un-served	served	served
136	2	856	Un-served	served	served
137	2	175	Un-served	un-served	served
138	1	100	Un-served	served	served
139	3	902.3	Un-served	served	served
140	3	100	Un-served	served	served
141	2	3191	Un-served	served	served
142	1	204.2	Un-served	un-served	served
143	1	377.4	Un-served	un-served	served
144	3	100	Un-served	served	served
145	2	3098	Un-served	un-served	un-served
148	1	100	Un-served	served	served
149	2	100	Un-served	served	served
150	3	3118	Un-served	un-served	served
151	3	1230	Un-served	served	served
152	3	406	Un-served	served	served
154	1	1066	Un-served	un-served	served
Total Loads		20615.2		48.36%	84.97%

Table 5.24: Loads status - WSCC 179-bus system - Zone 2-B

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5.3 Inter-zone scenarios

In order to demonstrate the effectiveness of the Inter-zone negotiation algorithms, we present several scenarios where the negotiation for the system restoration occurs in the Inter-zone level. First we have one modification of WSCC nine-bus system divided into two zones; as second scenario we present two modified WSCC nine-bus system interconnected, each system is a zone. Finally, we present a modification of the WSCC 179-bus system divided in five zones with some modification in power limits of the generators.

5.3.1 WSCC nine-bus system

The model used consists of a network of three generators, nine buses and three loads as depicted in figure 5.14. The system is divided into two zones:

- Zone 1 formed by generator 1, load 3 and buses 7, 1 ,6.
- Zone 2 formed by generators 2, 3; loads 1, 2; and buses 2, 3, 4, 5, 8, and 9.

The objective of this scenario is demonstrate the capacity of Inter-zone algorithms to supply loads when the intra-zone negotiation cannot do it.

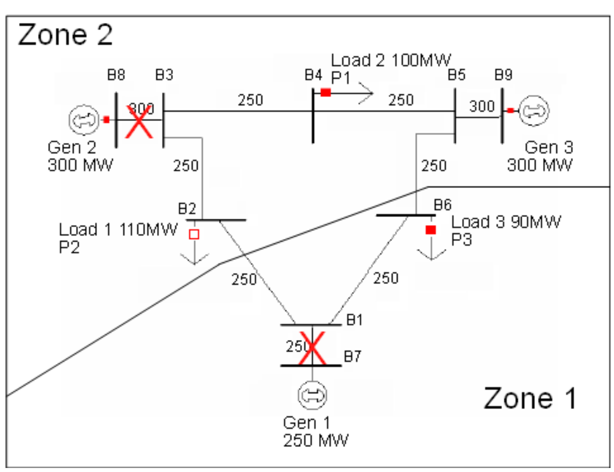

Figure 5.13: WSCC Nine-bus system - Inter-zone scenario

Results of simulation

After running the test cases four times, the power allocation negotiated by IPRs can supply 100% of the power required by loads in each case. After Intra-zone negotiation loads 1 and 2 are served but load 3 are not served because the generation capacity in Zone 1 is not enough to served. Then, load 3 sends a Inter-zone request across PPR 6, and PPR 5 gets this request and produces a intra-zone negotiation to supply this request. Finally generator 3 can supply the request and all loads of the system are served after inter-zone negotiation stage.

The allocation of power satisfies the constraints established in the mathematical formulation (section 3.2). Moreover, this allocation of power is done in de-centralized manner, using only local information. Table 5.25 presents the allocation of power for line in zone 1. and Table 5.26 presents the allocation of power for each line in zone 2.

Bus	Line	Limit	Status	Intra-zone	Inter-zone
B1	B1 - B7	250	Un-Available	0	0
	B1 B2	250	Available	0	0
	B1 B6	250	Available	0	0
B6	B5 B6	150	Available	0	90
	B1 B6	250	Available	0	0
	B6 - Load 3	90	Available	0	90
B7	B1 - B7	250	un-Available	0	0
	B7 - Gen 1	250	Available	0	0

Table 5.25: WSCC nine-bus system - Inter-zone scenario - Zone 1 - Bus and lines status

Bus	Line	Limit	Status	Intra-zone	Inter-zone
B2	B1 B2	250	Available	0	0
	B2 B3	250	Available	110	110
	B2 - Load 1	110	Available	110	110
B3	B3 - B8	300	un-Available	0	0
	B2 B3	250	Available	110	110
	B3 B4	250	Available	110	110
B4	B3 B4	250	Available	0	50
	B4 B5	250	Available	210	210
	B4 - Load 2	100	Available	100	100
B5	B5 - B9	300	Available	210	300
	B4 B5	250	Available	210	150
	B5 B6	150	Available	0	90
B8	B2 - B8	300	un-Available	0	0
	B8 - Gen 2	300	Available	0	0
B9	B5 - B9	300	Available	210	300
	B9 - Gen 3	300	Available	210	300

Table 5.26: WSCC nine-bus system - Inter-zone scenario - Zone 2 - Bus and lines status

Generator	Zone	Line	Limit	Status	Intra-zone	Inter-zone
Gen 1	1	B7 - Gen 1	250	Available	0	0
Gen 2	2	B8 - Gen 2	300	Available	0	0
Gen 3	2	B9 - Gen 3	300	Available	210	300

Table 5.27: WSCC nine-bus system - Inter-zone scenario - Generator status

Load	Zone	Priority	Value	Initial status	Intra-zone	Inter-zone
Load 1	1	2	110	Un-served	Served	Served
Load 2	1	1	100	Un-served	Served	Served
Load 3	2	3	90	Un-served	un-served	Served

Table 5.28: WSCC nine-bus system - Inter-zone scenario - Loads status

5.3.2 WSCC nine-bus system - interconnected two systems

The model used consists of a network of six generators, eighteen buses and six loads as depicted in figure 5.14. The system is divided into two zones, each one is a WSCC nine-bus system.

The objective of this scenario is demonstrate the capacity of Inter-zone algorithms to supply loads when the intra-zone negotiation cannot do it.

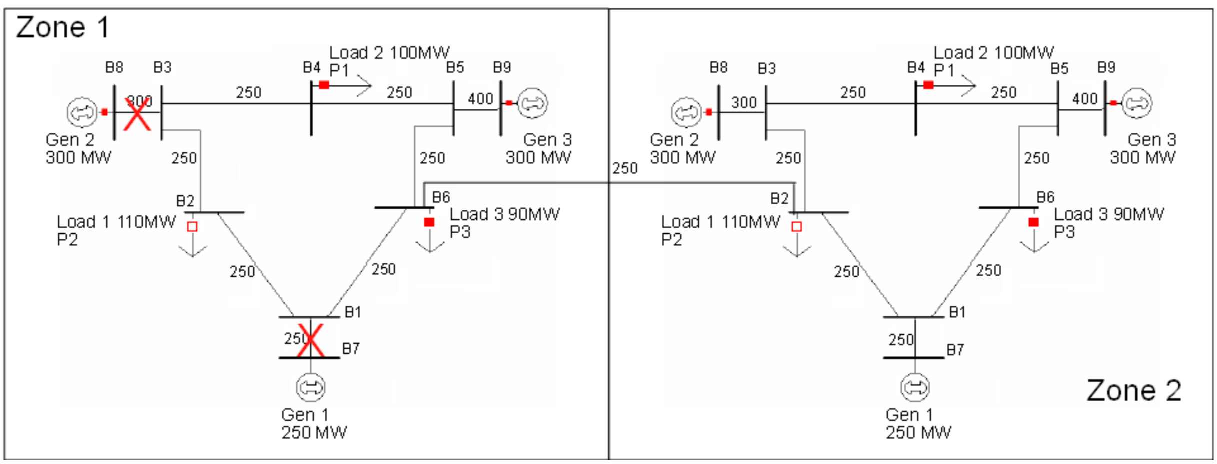

Figure 5.14: WSCC Nine-bus system - Interconnected two systems

Results of simulation

After running the test cases four times, the power allocation negotiated by IPRs can supply 100% of the power required by loads in each case. After Intra-zone negotiation in zone 1, loads 1 and 2 are served but load 3 are not served because the generation capacity in Zone 1 is not enough to served. While zone 2 reaches to supply its loads. Then, load 3 of zone 1 sends a Inter-zone request across PPR 6, and PPR 2 of zone 2 gets this request and produces a intra-zone negotiation to supply this request. Finally generator 2 of zone 2 can supply the request and all loads of the system are served after inter-zone negotiation stage.

The allocation of power satisfies the constraints established in the mathematical formulation (section 3.2). Moreover, this allocation of power is done in de-centralized manner, using only local information. Table 5.29 presents the allocation of power for line in zone 1. and Table 5.32 presents the allocation of power for each line in zone 2.

Bus	Line	Limit	Status	Intra-zone	Inter-zone
B1	B1 - B7	250	No Available	0	0
	B1 B2	250	Available	0	0
	B1 B6	250	Available	125	125
B2	B1 B2	250	Available	125	125
	B2 B3	250	Available	0	0
	B2 - Load 1	125	Available	125	125
B3	B3 - B8	300	un-Available	0	0
	B2 B3	250	Available	0	0
	B3 B4	250	Available	0	0
B4	B3 B4	250	Available	0	0
	B4 B5	150	Available	100	100
	B4 - Load 2	100	Available	100	100
B5	B5 - B9	400	Available	225	225
	B4 B5	150	Available	100	100
	B5 B6	250	Available	125	125
B6	B5 B6	250	Available	125	125
	B1 B6	250	Available	125	125
	B6 - Load 3	90	Available	0	90
	B6 - zone 2	250	Available	0	90
B7	B1 - B7	250	un-Available	0	0
	B7 - Gen 1	250	Available	0	0
B8	B2 - B8	300	un-Available	0	0
	B8 - Gen 2	300	Available	0	0
B9	B5 - B9	400	Available	225	225
	B9 - Gen 3	270	Available	225	225

Table 5.29: WSCC Nine-bus system - Interconnected two systems - Zone 1 - Bus and lines status

Generator	Line	Limit	Status	Intra-zone	Inter-zone
Gen 1	B7 - Gen 1	250	Available	0	0
Gen 2	B8 - Gen 2	300	Available	0	0
Gen 3	B9 - Gen 3	270	Available	225	225

Table 5.30: WSCC Nine-bus system - Interconnected two systems - Zone 1 - Generator status

Load	Priority	Value	Initial status	Intra-zone	Inter-zone
Load 1	2	125	Un-served	Served	Served
Load 2	1	100	Un-served	Served	Served
Load 3	3	90	Un-served	Un-served	Served

Table 5.31: WSCC Nine-bus system - Interconnected two systems - Zone 1 - Loads status

Bus	Line	Limit	Status	Intra-zone	Inter-zone
B1	B1 - B7	250	Available	90	0
	B1 B2	250	Available	0	0
	B1 B6	250	Available	90	90
B2	B1 B2	250	Available	0	0
	B2 B3	250	Available	125	125
	B2 - Load 1	125	Available	125	125
	B6 - zone 2	250	Available	0	90
B3	B3 - B8	300	Available	125	215
	B2 B3	250	Available	125	215
	B3 B4	250	Available	0	0
B4	B3 B4	250	Available	0	0
	B4 B5	150	Available	100	100
	B4 - Load 2	100	Available	100	100
B5	B5 - B9	400	Available	100	100
	B4 B5	150	Available	100	100
	B5 B6	250	Available	0	0
B6	B5 B6	250	Available	0	0
	B1 B6	250	Available	90	90
	B6 - Load 3	90	Available	90	90
B7	B1 - B7	250	Available	90	90
	B7 - Gen 1	250	Available	90	90
B8	B2 - B8	300	Available	125	215
	B8 - Gen 2	300	Available	125	215
B9	B5 - B9	400	Available	100	100
	B9 - Gen 3	270	Available	100	100

Table 5.32: WSCC Nine-bus system - Interconnected two systems - Zone 2 - Bus and lines status

Generator	Line	Limit	Status	Intra-zone	Inter-zone
Gen 1	B7 - Gen 1	250	Available	90	90
Gen 2	B8 - Gen 2	300	Available	125	215
Gen 3	B9 - Gen 3	270	Available	100	100

Table 5.33: WSCC Nine-bus system - Interconnected two systems - Zone 2 - Generator status

Load	Priority	Value	Initial status	Intra-zone	Inter-zone
Load 1	2	125	Un-served	Served	Served
Load 2	1	100	Un-served	Served	Served
Load 3	3	90	Un-served	Served	Served

Table 5.34: WSCC Nine-bus system - Interconnected two systems - Zone 2 - Loads status

5.3.3 WSCC 179-bus System

The model used consists of a network of 29 generators, 179 buses and 113 loads. The system is divided into five zones (1-A, 1-B, 1-C, 2-A and 2-B) as depicted in figure 5.15. In the original model several loads are network equivalents with a negative value, this means that in these section the generation exceeds the demand. For our simulation these loads with negative loads are generators. Then the number of generator increase while the number of loads decrease.

In this scenario in the Zone 1-B the generator 45 can operate only at 50% of its capacity. The transmission line between Zone 1-B and Zone 1-C is disconnected, and the following three lines in Zone 1-B are out-of-service:

- 36 - 85
- 159 - 158
- 162 - 161

With this configuration, the IPRs in Zone 1-B need to use Inter-zone negotiation to supply their loads because the local generators for Zone 1-B are unreachable for the loads.

The objective of this scenario is to restore the system after a total blackout. We worked with less Principal Power Routers than bus in the system because a PPR could manage one or more buses.

Results of simulation

After running separately several simulations for each zone, in a similar fashion to Intra-zone results, we obtain that in zones 1-A, 1-B,1-C and 2-A the IPR network could allocate resources every time to supply all loads. But in Zone 2-B the IPR network could allocate resources for 84% of loads in the best case and 76% of loads in the worse case but **every high-priority loads** are supplied in this zone.

In this case the loads 85, 161, 164, 165 and 166 of Zone 1-B are served by generators in Zone 1-A, because the capacity of the available lines in zone 1-B is not enough to supply theses with the generation capacity into this zone. Then, the Sink Power Router connected to Load 85 sends a set of Inter-zone requests, and this request is answered by generators in the Zone 1-A (a zone rich in generation).

The allocation of power satisfies the constraints established in the mathematical formulation (section 3.2). Moreover, this allocation of power is done in de-centralized manner, using only local information.

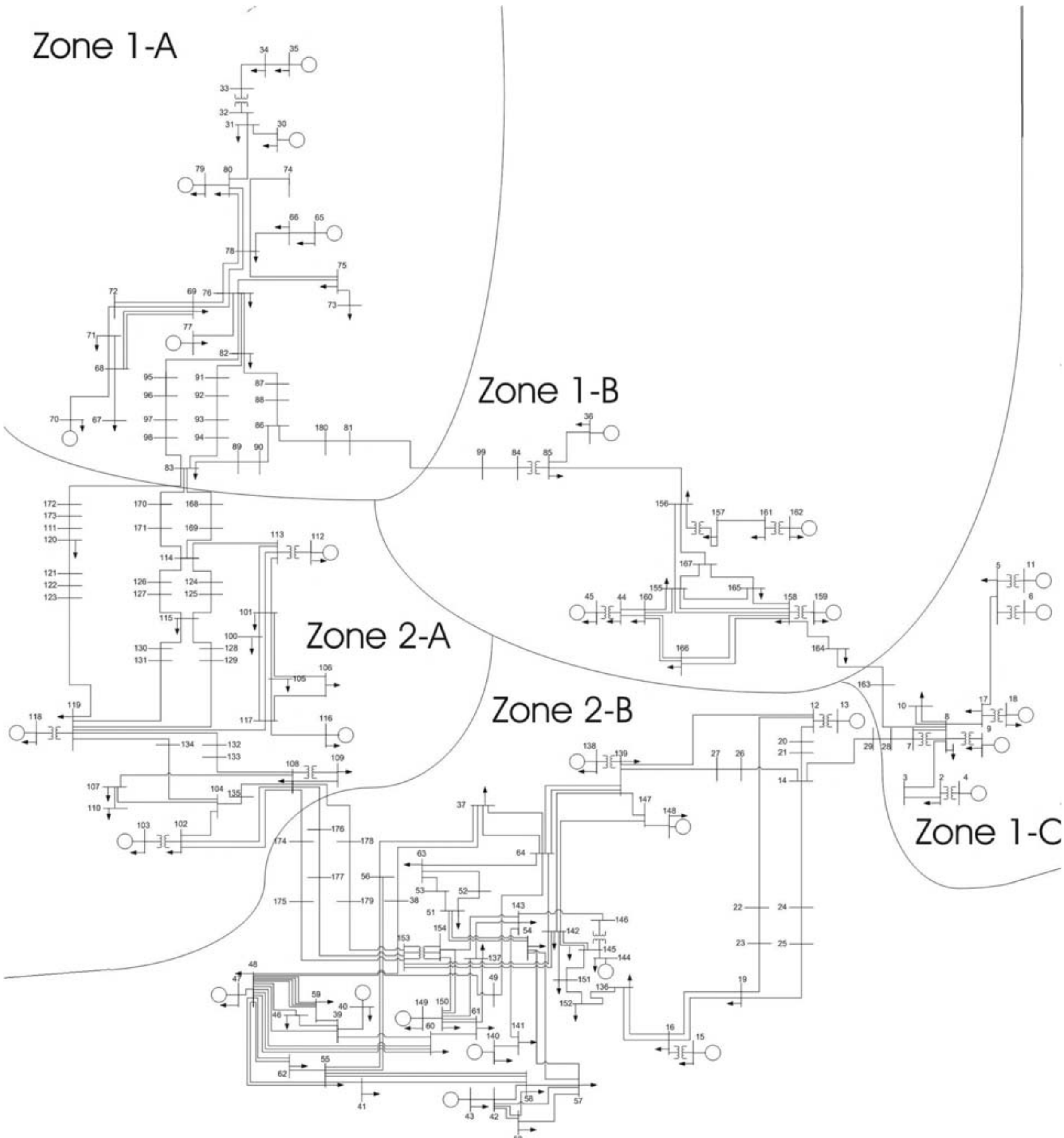

Figure 5.15: WSCC 179-bus model

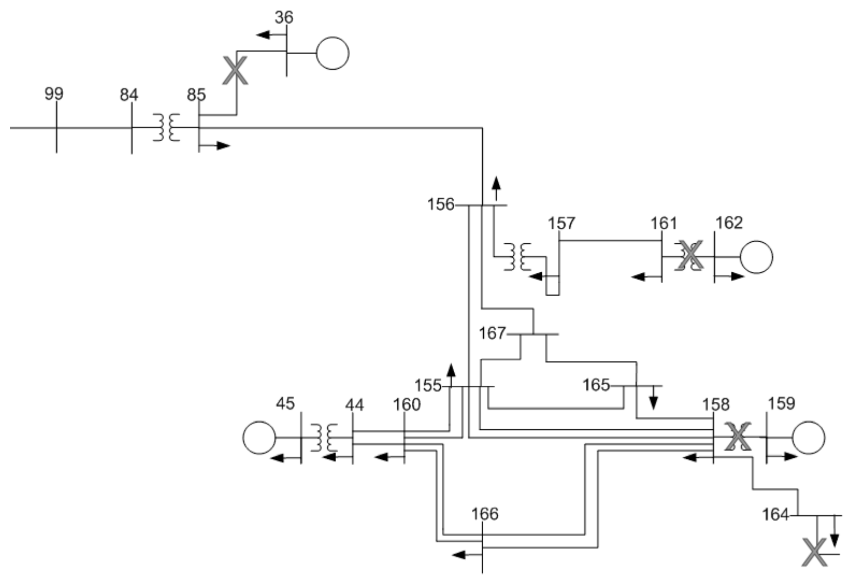

Figure 5.16: WSCC 179-bus model - Inter-zone scenario - Zone 1-B

Table 5.35 presents the power allocation for generators in Zone 1-A and Table 5.36 presents the power allocation for generators in Zone 1-B. In these tables the Column "Generator" corresponds to the Identifier of each generator. The column "Line" corresponds to the power line that connects Generators with its bus. The column "limit" corresponds to Generator Capacity, column "Status" corresponds to Availability of each generator. And the column "Final" corresponds to power allocation for each generators. In this section we present only results for Zones 1-A and 1-B, because the others zone have similar results as we presented in section of Intra-zone results.

The Table 5.37 presents the status of each Load in this zone during the negotiation process for the Zone 1-A. The column "Load" corresponds to the bus where the load is connected. The column "Priority" corresponds to the Load Priority. The column "Initial Status" corresponds the Initial status after the blackout and Columns "Friendly stage" and "Persistent Stage" correspond to the Load status after each negotiation stage respectively.

The Table 5.38 presents the status of each Load in this zone during the negotia-

Generator	Line	Limit	Status	Final
Gen 30	B 30 - Gen 30	10000	Available	4500
Gen 35	B 35 - Gen 35	10000	Available	3700
Gen 65	B 65 - Gen 65	10000	Available	5135.2
Gen 68	B 68 - Gen 68	67.5	Available	0
Gen 69	B 69 - Gen 69	44.2	Available	0
Gen 70	B 70 - Gen 70	10000	Available	972
Gen 73	B 73 - Gen 73	1525	Available	0
Gen 77	B 77 - Gen 77	10000	Available	5003.6
Gen 79	B 79 - Gen 79	10000	Available	9987
Gen 82	B 82 - Gen 82	66.6	Available	0
Gen 83	B 83 - Gen 83	339	Available	0
Total Generated				29297.8

Table 5.35: WSCC 179-bus system - Zone 1-A (Inter-zone scenario) - Generators status

Generator	Line	Limit	Status	Final
Gen 36	B 36 - Gen 36	10000	Available	100
Gen 45	B 45 - Gen 45	5000	Available	3093.7
Gen 159	B 159 - Gen 159	10000	Available	100
Gen 160	B 160 - Gen 160	62	Available	0
Gen 162	B 162 - Gen 162	10000	Available	100
Total Generated				3393.7

Table 5.36: WSCC 179-bus system - Zone 1-A (Inter-zone scenario) - Generators status

Load	Priority	Value	Initial status	Friendly stage	Persistent Stage
30	2	100	Un-served	Served	Served
31	3	4400	Un-served	Served	Served
34	2	3600	Un-served	Served	Served
35	3	100	Un-served	Served	Served
65	3	100	Un-served	Served	Served
66	3	1700	Un-served	Served	Served
67	3	160	Un-served	Un-served	Served
70	3	100	Un-served	Served	Served
71	3	3137	Un-served	Un-served	Served
75	3	2584	Un-served	Un-served	Served
76	3	3200	Un-served	Served	Served
77	3	100	Un-served	Served	Served
78	1	3500	Un-served	Un-served	Served
79	2	100	Un-served	Served	Served
80	2	5000	Un-served	Served	Served
Total Loads		27881		66.35%	100%

Table 5.37: WSCC 179-bus system - Zone 1-A (Inter-zone scenario) - Loads status

tion process for the Zone 1-B. The column "Load" corresponds to the bus where the load is connected. The column "Priority" corresponds to the Load Priority. The column "Initial Status" corresponds the Initial status after the blackout and Columns "Intra-zone phase" and "Inter-zone phase" correspond to the Load status after each negotiation phase respectively. Notice that Loads 85, 161,164,165 and 166 still un-served after Intra-zone, but after Inter-zone phase these loads are served.

Load	Priority	Value	Initial status	Intra-zone phase	Inter-zone phase
36	2	100	un-served	served	served
44	1	2053	un-served	served	served
45	3	100	un-served	served	served
85	1	610	un-served	un-served	served
155	3	457.7	un-served	served	served
156	3	33.9	un-served	served	served
157	3	148	un-served	served	served
158	3	116.1	un-served	served	served
159	1	100	un-served	served	served
161	2	255	un-served	un-served	served
162	3	100	un-served	served	served
164	1	31.6	un-served	un-served	served
165	2	141.2	un-served	un-served	served
166	3	379	un-served	un-served	served
167	2	185	un-served	served	served
Total Loads		4810.5		70.4%	100%

Table 5.38: WSCC 179-bus system - Zone 1-B (Inter-zone scenario) - Loads status

5.4 Experimental results summary

In this chapter, we have presented several simulation scenarios to demonstrate the effectiveness of our IPRs Negotiation. These scenarios are organized in two groups, Intra-zone scenarios and Inter-zone scenarios. In every scenario the IPRs obtain successfully the reservation of power needed to supply all loads or at least the high-priority loads.

CHAPTER 6

Conclusion and Future Work

Every social and economic function of our society is highly dependent on Electrical Energy Delivery Networks - EEDN, therefore its high reliability is always required. Currently, to make the EEDN tolerant to failures and improve their reliability, Power Delivery Systems are designed with redundant power generators and delivery lines. However, the decision for system control and coordination are made in a centralized manner from only a few sites (controls centers). This centralized scheme has a clear drawback: a failure in one of these control centers might result in the total collapse of the system.

In this thesis, we have presented a new model for Power System Restoration based on a distributed concept with scalable coordination using Intelligent Power Routers (IPRs). Obviously, these IPRs need a robust control protocol for guarantee an optimal system performance. In this thesis, we have presented several restoration strategies embedded into IPRs. The restoration protocol and decision algorithm are based in the reliability factor for inputs lines and priority factor for input lines. Also, we added a multi-stage negotiation scheme as a important characteristic to improve IPRs performance, scalability and quality of decisions. Moreover, we have presented a prototype of IPRs network that has a good performance for system restoration in many scenarios using the test-bed systems designed by

Western Systems Coordinating Council - WSCC. In particular, our intra-zone negotiation protocols were able to restore eiher all loads or the most critical ones 100% of the time. Likewise, the inter-zone negotiation protocols were able to restore most of the loads in the WSCC 179-bus system. This demonstrates the feasibility of using IPRs as the elements that can direct the restoration of the system in a de-centralized manner.

In this chapter, we present a summary of the main results and contributions of this thesis. In addition, we offer a set of future directions for IPRs development.

6.1 Summary of Contributions

In this research the major contribution is the development of a completely distributed framework to solve the problem of Electrical Power System Restoration. Traditionally, this problem has been resolve using centralized solutions, with the risk associated to this approach. In our framework, the intelligence that can be used for control and coordination operations is embedded into a series of computing devices called the Intelligent Power Routers (IPRs)[1]. These IPRs are strategically connected to power generators and power lines, thus enabling them not only to observe current network conditions, but also cooperate with each other to actively alternate lines to move power from producers to consumers.

In chapter 3, we presented our Mapping of Electrical Energy Distribution Networks (EEDN) to a Wide Area Network (WAN) with the similarities between WAN elements and EEDN elements. Additionally in that chapter, we presented our mathematical formulation with our objective function and model constraints to maintain physical considerations for Electrical Power Systems. Also, we have presented our IPR Network Architecture as a peer-to-peer network. In this architecture, it is irrelevant whether its inputs come directly from power producers or other IPRs. The key to our approach is to provide multiple redundant power paths between producers (generators) and consumers (loads). Finally, we have presented the split request scheme to improve the IPRs performance increasing the number of possibilities of paths to supply the Load requests.

Chapter 4 presents the Island-zone approach for controlling the number of messages travelling on the network. With this approach the system is divided in several zones. Each zone is a sub-system with generators, buses and loads that need to be restored. The restoration scheme developed in that chapter is divided in two phases. The first phase (Intra-zone Phase) is designed to perform the restoration process using the local resources in each zone. And the second phase (Inter-zone Phase) is the restoration process using the capacity in the neighboring zones. Additionally, in chapter 4 we have presented the necessary message types to perform the restoration process using the IPR negotiation scheme.

The effectiveness of IPR negotiation scheme, for the restoration process in a decentralized form, was presented in chapter 5. Chapter 5 presents several simulation scenarios using the test-bed systems designed by the Western Systems Coordinating Council - WSCC. This simulation scenarios are divided into two groups. The first group is oriented to demonstrate the effectiveness of Intra-zone negotiation scheme and the second group is oriented to demonstrate the effectiveness of Inter-zone negotiation scheme. Finally, the effectiveness of the IPR Negotiation Scheme is demonstrated in every scenario, since the IPRs where able to successfully obtain the reservation of power needed to supply all loads (in most of the cases), or at least for the high-priority loads.

In summary, in this thesis we have presented a new scheme to perform in a distributed and decentralized form for the restoration process for Electrical Energy Delivery Networks, available for Transmission and Distribution systems.

6.2 Future Work

We have proposed future work to improve the quality of decision and IPRs performance:

1. The next step of this research must be oriented to calculate the reliability and priority factors dynamically and adaptively while system conditions change. The response time of the IPR Negotiation is associated with the speed of IPR Network to establish the adequate path between generators and loads. Notice that if the reliability and priority factor reflect the real system conditions all the time, then the IPRs do not waste time searching through low-reliability possibilities.

2. We propose to involve other characteristics of the Electrical Power Systems such as reactive power, system frequency and system voltage in the IPRs negotiation scheme. In this thesis we present the IPRs negotiation scheme for system restoration but on a high abstract level, to deploy these concepts in the physical systems it is necessary to considerate other physical characteristics of Electrical Power Systems. In addition, it is necessary to implement the mechanisms necessary to perform the switching operations that enable the power flows that the restoration plan specifies (which the IPRS generate).

3. We propose modify the negotiation scheme to permit the partial restoration of the loads. In power systems is possible restored a portion of a given load, because generally each load is representing a set of loads.

4. Finally, our IPRs must pre-compute a set of contingency plans to improve their response time with information about historical contingencies. These contingency plans will be based on reserving resources, such as portions of line capacity, for each IPR across the network.

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APPENDICES

APPENDIX A

Multi-stage Negotiation algorithms

A.1 IPRs Negotiation algorithms

In section 3.6 we presented the basic negotiation schema, in this section we present the complex negotiation schema involving IPR negotiation process is in two phases.

A.1.1 Intra-zone algorithms

The algorithms for intra-zone phase are designed to perform negotiation in a Friendly and a Persistent stages. In the friendly stage the negotiation is performed as described in section 3.6.

Below we present the algorithms for Persistent and Load shedding stage divided in three section: for Sink PR, for Source Pr and for Principal PR.

For Sink Power Routers (Snk Pr):

```
Send a Persistent Get Message

Wait for response
```

```
if response is a Put Message
    connect load
else
    Send a Mandatory Get Message
    Wait for response
    if response is a Put Message
        Connect load
    else
        Begin Inter-zone process
    end if
end if
```

For Source Power Routers (Src Pr)

```
Wait for message
if message is a Persistent Get Message
    Check Generator Capacity
    if Generator can supply request
        send Put Message
    else
        send a Denied Message
    end if
else
    if message is Mandatory Get Message
        if Src PR can supply request disconnecting
        low-priority served loads
            send Disconnect Messages
```

```
        Wait for Disconnect Confirmation Messages
        Allocate resources for request
        send Put Message
    else
        send Denied Message
    end if
  end if
end if
```

For Principal Power Routers

```
main function
  Wait for message
  select message Type case
    case Persistent Get Message:
        process Persistent Get Message
        break
    case denied message
        process denied message
        break
    case Put message
        process put message
        break
    case Disconnect Message
        process Disconnect Message
        break
    case Disconnect Confirmation Message
        process Disconnect Confirmation Message
```

```
                break
        case Mandatory get message
                process Mandatory get message
                break
        case Mandatory change message
                process change message
                break
    end select case;
end function

function process Persistent Get Message
    Check source message priority
    Store the message in request queue
    Send a Status Request to all others clients
    with higher priority asking their status.
    Wait time T to acquire responses.
    For each response
        If response is not normal status
            Store the message in request queue
        End if
    Change output lines to input lines if it is possible
    For each message in request queue
        Repeat until get an OK response or obtain
        deny message from all power supplier
        Adjacent IPR
            If link capacity can support more power flow
                Send get message to IPR with most
```

```
                reliable line not yet inspected
                Wait for response
                If OK response
                    Send Ok response to client
                End if
                If IPR obtains deny message from all IPRs
                    Send Denied Message to client
                End if
            End if
        End repeat
end function


function process Denied message
    check pending queue for original request
    if original request is a split request
        Send denied message to client
        Send disconnect confirmation across input line with
        affirmative response
        de-allocate resources allocated for this request
    else
        Check available capacity in input lines
        if available capacity >= request value
            Split request
            send partial requests across selected lines
        else
            Check lower-priority served requests than actual
            request
```

```
            if lower-priority served request value >= actual
            request value
                Send requires Disconnect Messages
                for each Disconnect Message
                    Wait for Disconnect Confirmation Message
                    process Disconnect Confirmation Message
                Send requires Mandatory Change Message
            else
                Send Denied Messages to client
            end if
        end if
    end if
end function

function process put message
    check pending queue for original request
    if split request
        set input line with affirmative response
        check for others input lines involved in actual
        request
        if every involved input lines have affirmative
        response
            Allocate resources
            send Put Message to Client
        else
            Wait for others responses
        end if
```

```
    else
        Allocate resources
        send Put Message to Client
    end if
end function


function process Disconnect Message
    route disconnect message across appropriated output lines
end function

function  process Disconnect Confirmation Message
    route Disconnect Confirmation Message across appropriated input lines
    de-allocate appropriated resources
end function

function Mandatory get message
    Check lower-priority served requests than actual request
    if lower-priority served request value >= actual
    request value
        Send requires Disconnect Messages
        for each Disconnect Message
            Wait for Disconnect Confirmation Message
            process Disconnect Confirmation Message
        Send requires Mandatory Change Message
    else
        Send Denied Messages to client
```

```
    end if
end function

function Mandatory Change Message
    Check objective request that was disconnected
    Change appropriated parameters to allocate resources
    for actual request
    send Mandatory Change message across appropriated
    input lines
end function
```

A.1.2 Inter-zone algorithms

For the Inter-zone negotiation schema we have designed the following algorithms. In this phase are involved only Sink Power Routers and Principal Power Routers.

For Sink Power Router

```
Send a Inter-zone Request Message
Wait for response
if response is a Put Message
    connect load
else
    begin a Intra-zone Process
end if
```

For Principal Power Routers we use Basic negotiation algorithm modified with condition if it is a Border Power Router it must send a Inter-zone Get Message.

```
Wait for message
if message is a Inter-zone Request
    if actual Power router is a Border Power Router
        send a Inter-zone Get Message
        Wait for response
        If a Put Inter-zone message
            send a put message to client
        else
            Route the message as an Intra-zone message until
            reach another Border Power Router or get a
            intra-zone response(put or denied message)
        end if
else
    if message is a Inter-zone get message
        begin Intra-zone negotiation process
        wait for a Intra-zone response
        if Intra-zone response is a Put message
            send a Inter-zone Put message to original zone
        else
            send a Inter-zone Denied message to original zone
        end if
    else
        message is an Intra-zone request and it must be routed
        with intra-zone algorithms
    end if
end if
```