Chapter $1$

**Intelligent Power Routers: Distributed Coordination for Electric Energy Processing Networks**

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**Editors’ summary:** This chapter presents a new concept for controlling the generation units of a power system that is able to achieve improved performance in security, reliability, and reconfigurability. The authors investigate imbedded intelligent power routers that are able to perform line switching, load shedding, and the broadcast of local state information about system statuses for the energy management system (EMS). The architecture of the proposed intelligent router is based on fundamental engineering design based on modular decentralized control concepts. The scheme has been tested using selected benchmark systems.

$.1$ Introduction
The Intelligent Power Router (IPR), a concept based on scalable coordination, is proposed to control the next generation power network. 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. Each IPR has embedded intelligence into them allowing it to switch power lines, shed load, and receive/broadcast local state variable information to and from other IPR. The information exchange capability of the routers will provide coordination among themselves to reconfigure the network when subject to a natural or man-made disaster.

In this work we report our progress on six different activities around the creation of the IPR; IPR architecture, Communication Protocols among IPR, distributed controls, risk assessment of a system operated with and without IPR, power system reconfiguration based on a controlled islanding scheme using IPR and the definition of the power routing as an ancillary service since the IPR may provide improved efficiency and security in the context of a realistic market structure such as the Standard Market Design, with LMP pricing algorithm.

$.2$ Overview of the Intelligent Power Router Concept

Existing Power Delivery Systems are designed with redundant power generators and delivery lines to make the system tolerant to failures on these elements. However, the control and coordination of the process to generate and distribute power still occurs in a centralized manner, with only a few sites, or even one site, managing power generation and delivery. This scheme has a clear drawback: a failure in one of these control centers might impair the system. Therefore, it is highly desirable that future Power Delivery Systems has the capability of distributing the task of coordination and control of power generation and distribution when contingencies or emergency situations occur.

We are developing a model for the next generation power network control using a distributed concept based on scalable coordination by an Intelligent Power Router (IPR). 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. Our approach builds on our knowledge from power engineering, systems, control, distributed computing, and computer networks to propose a power network concept that will meet the desired objectives.

In our proposed scheme control can be detached from central control sites, and delegated to intelligent power routers (IPR) that are strategically distributed over the entire Electric Energy Processing Network. Each power router has embedded intelligence into them, and by intelligence we mean programmability, allowing the power router to switch power lines, shed load based on a priority scheme, activate auxiliary or distributed generation, isolate power region of the energy delivery network to prevent system cascade failures and receive/broadcast local state variable information to and from other routers. The information exchange capability of the routers provides coordination among themselves to reconfigure the network, even when the designated principal control center of the system has collapsed due to a natural or man-made disaster. The IPR may achieve their task using direct monitoring, area-limited on-line security assessment and adaptive reconfigurable controls to establish a coordinated and local set of control actions to
either apply preventive countermeasures prior to a potential disturbance or corrective countermeasures following a disturbance.

Our proposed approach follows a data routing model in computer networks, where data can be moved over geographically distant nodes via *data routers* (or simply routers) [2][3][4]. When a flow of data needs to be established between two end points, the routers cooperate by moving pieces of data over the network until the data reaches the desired destination(s). At each step of this process, a router that receives a packet of data determines the next router that shall forward that fragment of data. Notice that there might be many candidate routers, but the one that can do the best forwarding job is the one that is selected. In our view, a Power Delivery System could operate in similar fashion with due consideration of the physical differences between data exchange and energy exchange. In the event of a component or system failure, the IPR will make local decisions and coordinate with other routers to bring the system, or part of it, back into an operational state allowing the system to operate in degraded operation during major contingencies. The proposed scheme will not substitute current control protocols if there are no contingencies. However, under normal operating conditions, the IPR would provide additional information on system status to the central energy management system.

**Figure S-1:** IPR exchange information and take local decisions to avoid cascade failure when facing a major disturbance, natural or man-made

Figure S-1 presents the system we envision. Generation units $P_1, P_2, \ldots, P_n$ are connected via the power network with consumers $C_1, C_2, \ldots, C_m$. The producers and the consumers are connected via a series of power lines and intelligent power routers, $R_1, R_2, \ldots, R_k$ which take on the role of controlling the routing of power over their lines when a major system disturbance occurs.

As Figure S-2 shows the IPR receives sensor data, process the information, take decisions and commands flow control devices. The routers are organized in a network managing multiple redundant power paths between producers and consumers. The IPR organization is based in a Peer-to-Peer system (P2P) or a mesh.

Each IPR maintains information on the power flowing through each of its connecting power lines. This information is used to make local decisions on how to re-route power in the event of changes in the amount of power moving along the lines, which might be caused by failures, changes in power generation or demand. These routers may also signal that emergency power sources are needed on-line to meet demand and may gracefully bring down portions of the
system in order to avoid further damage in the event of a contingency and maintain service to critical loads.

Figure 5-2: Proposed architecture for the Intelligent Power Router

Notice that this approach is a departure from state-of-the-art schemes since the power network has the infrastructure to react to changes in a decentralized and autonomous fashion. The power network has enough redundancy and intelligence to find alternate paths to deliver power to the loads. The goal of the network is to **survive** failures, and returns critical loads to an acceptable level of operation. To achieve this, our approach reduces the risk associated with single-points of failures by using the IPR a mechanism to operate the system following a distributed control scheme.

Intelligent power routers are fundamental building blocks for the control scheme of the power distribution system that we are proposing. IPR will be strategically distributed over a power delivery network, a metropolitan area or a naval ship, that has been divided into several sectors, each one served by at least two routers. These IPR can then be connected to a second layer of IPR that are in charge of controlling power delivery on the scale of regions formed by two or more sectors. These, routers can in turn connect to a group of backbone routers that are directly connected to the power generators.

Our long-term goal is to architect a new type of scalable and decentralized power distribution infrastructure based on the concept of the IPR. This architecture should provide sustained operation in the presence of partial failures to power sources and communication lines thru automatic reconfiguration. The fundamental engineering design principle behind the IPR system is *modular decentralized control*. An IPR can be used as a simple yet fundamental building block upon which complex power distribution networks can be engineered in a disciplined fashion. Our **design objectives** are:

- **Survivability and Fault Tolerance** - Decentralized IPR modules control power routing based on local information. IPR capable of isolating failures.
- **Scalability** - IPR can be composed with other IPR to create complex distribution networks. The system can grow incrementally. Architecture admits graceful profile-based reengineering.
- **Cost-effectiveness** - Decentralized IPR modules avoid having to connect very producer to every consumer directly. Economies of scale reduce the cost of IPR.
• *Unattended 24/7 Operation* - IPR are equipped with programmable computing capabilities. IPR incorporates algorithms that allow reconfiguration decisions without human intervention.

The rest of the paper is organized as follows: Section $.3$ presents the project objectives, Section $.4$ shows the relation of the proposed work to the present state of the art in the field and work in progress, Section $.5$ discusses current IPR Architecture and Software Module, Section $.4$ presents IPR Communication Protocols, Section $.7$ shows Risk Assessment of a system that operates with IPR, Section 7 studies Distributed Control Modules, Section 8 explores the idea of defining the rendering of efficiency and security provided by IPR as an ancillary service, Section 9 shows some of our education effort and Section 10 presents final remarks and outlines future work.

$.3$ IPR Architecture and Software Module

The main goal of this component of the project is to design and test architecture for the IPR, the backbone of the new type of energy distribution network that we propose. Central to this architecture is the notion that IPR should eventually evolve into a new type of off-the-shelf component that energy network designers can use as building blocks in the construction of networks of all levels of complexity and capacity.

An IPR is in essence an energy flow controller with programmable intelligence. Figure $.2$ shows a proposed architecture for an IPR consisting of two main components: Interfacing Circuits (ICKT) that operates existing Energy Flow Control and Sensing Devices (EFCD), and an Intelligent Control and Communication Unit (ICCU). Example of EFCD’s are: circuit breakers, phase shifting transformers, series compensation capacitors or their combination as Flexible AC Transmission (FACTS). The ICKT is the hardware component that interacts with the energy transfer components of the electric power system. Many devices that could act as EFCD’s in an IPR-based system are already available in the market. They will work by controlling the power flow, opening and closing lines as needed, or regulating the amount of power that flows through a given interface. The Interfacing Circuits sends commands to the EFCD to dynamically change the behavior of the power system. Also, the ICKT receives information collected by sensors (CTc, PTs) and Dynamic System Monitors (DSM) on the system state (phase currents, bus voltages, system frequency, generation levels, etc.) to assess the current status of the system.

The ICKT will operate under the direct control of the ICCU, which will have the necessary logic and software to determine how to re-route power, change load set point in generators, shed load or take any other corrective or preventive action to enhance system security. The ICCU can be implemented as an embedded computer located inside the IPR and could feature a RISC-type CPU, high speed RAM, non-volatile data storage and a network interface. The ICCU should be made out of commodity components to keep its cost low, make it easy to fix or replace, and to leverage on the latest advances in the computing technology. For example, the ICCU can run the latest version of the LINUX operating system for embedded systems. This scheme will not only make the IPR fully programmable, but also simpler to upgrade with new versions of the system software. In short, the Intelligent Power Router consists of two distinct elements: the Intelligent Control and Communication Unit (ICCU) and
the Interface Circuits (ICKT). Existing energy flow controls and sensors will be managed by the IPR.

Figure 3-3: A simple switch-based IPR system.

Figure 3-3 shows a simple switch-based IPR system that can illustrate the potential for survivability of an IPR-based network. For simplicity let’s assume that each of the two sources can supply exactly one of the loads. In an ordinary power network and upon failure of a source the system will attempt to continue serving both loads. This may result in a total failure since none of the loads will receive enough power to operate. In an IPR system, the ICCU can react to the source failure by reconfiguring the network in order to serve the load with higher priority with the power supplied by the surviving source. Load priorities may serve to model levels of criticalness or perhaps level of power quality purchased by different customers. Key to the IPR system is the ability to assign these priorities dynamically and without requiring costly and slow physical re-configuration of the network. Our goal is to discover distributed algorithms that so not require centralized control of a complex network with potentially many IPR’s. The modularity of IPR’s will make it possible to create configurations significantly more complex than the one shown above requiring neither hardware modifications nor ad-hoc devices.

Figure 3-4 shows a Virtual Test Bed (VTB) [16] simulation of the system shown in Figure 3-3. The IPR module at the center of the figure continuously receives readings from current sensors connected to each of the two power sources. Initially, the left source serves the left load and the right source serves the right load. The sinusoidal plot on the upper right shows the current drawn from the left source. At some point during the simulation the left source fails and stops generating current. The lower right plot depicts the current fed into the left (higher priority) load. In response to the failure of the left source the IPR re-configures the switches in order for the right surviving load to serve the left load. Therefore the current into the left load is restored after a short transient period. The goal of the IPR-based system is to harness the laws of physics in order to control energy flows based on dynamically reconfigurable load priorities with minimal human intervention.
Our next challenge was to find an appropriate simulation framework allowing us to conduct experiments in a setting significantly more realistic than the one used for experimentation with the initial version of the IPR model illustrated above. We wanted, for instance, to work with realistic models of power generation sources and loads, as well as with more realistic models of switches and faults. The most suitable framework available to us was the SimPower power system simulation package available for MatLab.

To gain experience with the new simulation environment we developed the simple model of a 3-bus power system depicted in
Figure S-5: The system consists of two generators and a single load. Each load is controlled by an IPR for a total of 3 IPRs (light blue boxes). We also designed a fault injection module (green in
Figure 6--5) that automatically generates a line-to-ground fault on phase A after a pre-specified amount of time. This is an initial experiment and in the future other types of faults will be added to the model. The fault detection circuitry (dark blue in Figure 6--5) detects the line-to-ground fault by computing the zero-sequence component of the 3-phase signal. Part of this circuitry will eventually be packaged inside the IPR module. In particular, the portion of the circuitry that determines the action to be taken in response to the fault will be part of the IPR. Right now, this portion of the circuitry is essentially inexistent since the very output of the zero-sequence analyzer is used to drive a relay that controls the switches that interconnect the two relevant buses. Although rather simplistic, this framework allows us to experiment with more complex IPR logic by inserting appropriate logic components between the zero-sequence analyzer and the relay.
Figure S-5: A SimPower model of a 3-bus System with 3 IPR Modules

Figure S-66 shows the current at lines labeled A, B, C and D in A

IPR Modules

D
After a short transient power supply to the load is reestablished. After about 100ms the fault is fixed and the zero-sequence analyzer deactivates the relay causing the breaker to close again. As depicted in Figure S-66 the current in line A raises to its pre-fault level and the system overall is reestablished to its initial configuration.

Once we gained enough experience with the simulation framework we shifted our focus to the creation of a modular SimPower model for an IPR and its application to the design of shipboard electric systems. After considering different shipboard models proposed in the literature we decided to base our work on the DD(X) Navy Test Bed model developed at the University of Texas Center for Electromechanics. Due to the unaccessibility of the SimPower model for the Test Bed, we proceeded to assemble the model depicted in

Figure S-7: This model uses realistic models of turbine generators, engines and other loads typically found on Navy ships.

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1 http://www.utexas.edu/research/cem/
The model that we have developed uses a new type of computer controllable bus (large buses towards the lower center of

![Diagram](image_url)

**Figure S-6:** Current at indicated points in the example 3-bus system

This bus serves the purpose of the EFCD in the IPR architecture. The internal structure of the controllable bus is shown in Figure S-8 and it includes sensor and actuator circuits that will be controlled by the ICCU. We are currently developing the IPR intercommunication subsystem that will enable the implementation of the IPR protocols that will be the topic of the following section.

**Figure S-7:** This bus serves the purpose of the EFCD in the IPR architecture. The internal structure of the controllable bus is shown in Figure S-8 and it includes sensor and actuator circuits that will be controlled by the ICCU. We are currently developing the IPR intercommunication subsystem that will enable the implementation of the IPR protocols that will be the topic of the following section.
Figure S-7: SimPower Model of DD(X) Shipboard Power System

Figure S-8: SimPower Model of 3-phase computer controllable bus

§.4 IPR Communication Protocols

§.4.1 Current State-of-the-Art

In our framework for self-healing electrical networks, the intelligence used for control and coordination operations is embedded into the IPR. As shown in Figure S-9, IPR are computing devices strategically deployed over the electric network at buses, power lines,
power generators, and close to loads (i.e., power consumers). By controlling electronic power flow control devices (e.g., switches, FACTS), IPR can “route” power to various areas in a similar fashion as routers forward packets in a computer network. For example, when power is lost on a given region due to a generator failure, several IPR in charge of that region might request another generator to increase its power output, and then coordinate to close alternate lines to route power into the affected region. Likewise, IPR can oversee load shedding operations to remove low-priority loads (e.g., theaters) from the system in favor of other loads with higher priorities (e.g., hospitals). Groups of IPR are responsible for executing distributed algorithms for disseminating system status information among fellow IPR, and for using this information in making local decisions in the event of system failures. During a contingency, groups of neighboring IPR work together to contain the damage, bring back critical lines, activate emergency generators, deliver power to critical loads, and continuously monitor the system to maintain an acceptable level of operation. 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 of the electrical network.

An IPR-based power delivery system scales much in the same way as a computer network scales. Groups of local IPR form “local area power networks” and are interconnected by border IPR, which enable the formation of larger networks of networks. Meanwhile, border IPR are responsible for attempting to contain countermeasures and recovery actions inside local area power networks to avoid failures from cascading across large regions of the system. IPR view currently existing relay-based load shedding schemes as lower layer countermeasures in a multi-layer power delivery network.

Figure 5-9: Electrical Network Featuring IPR

$4.2$ Restoration of Electrical Energy Networks with IPR

When an unforeseen contingency occurs, the worst scenario that can happen is a system blackout (e.g., August 2003 Northeast USA Blackout), in which either the whole
system or large sections of it are rendered inoperable. After such event, a restoration process is needed to bring the system back into operation. This process involves determining the right order of reconnection steps necessary to re-energize power generators, transmission lines, distribution lines, and loads. Typically, this problem has been modeled as a Network Flow graph optimization problem [8]. We now discuss how IPR can be used to find a restoration plan in a decentralized manner, in contrast to existing centralized schemes.

**S.4.3 Mathematical Formulation**

Our mathematical model is a modification of a mathematical formulation presented in [22][23]. The objective of the mathematical model for our power system restoration approach is to maximize the number of restored loads having the highest priority values. Our objective function is given by the following mathematical expression:

$$\max \sum_{k \in R} L_k \cdot y_k \cdot (\alpha - Pr_k)$$

Where $Pr_k$ is the load’s Priority factor (the highest priority load will have $Pr = 1$, the second priority load will have $Pr = 2$ and likewise the other loads), $\alpha$ is a natural number larger than the $Pr$ value with 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 $L_k$ no restored), and $R$ defines the current set of de-energized loads. The constraints associated with our mathematical model are similar to the constraints in the restoration model presented in [22]: a) limits on power sources available in each bus for restoration, b) balance in the Power System between supply and demand, and c) limits on line capacity for power transmission.

**S.4.4 IPR Network Architecture**

The IPR are organized in a peer-to-peer (P2P) network [9][11][12]. In this architecture, for a given IPR, it is irrelevant whether its inputs come directly from power producers or other IPR. For this propose, we assume that there is one IPR in each of the buses in the system. An important issue to realize is that the network for transmission or distribution of electrical energy is different from the communications network between IPR. 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. For this purpose, we put an IPR in each bus of the system. Figure S-10 shows the relation between the Electric Energy Delivery Network (EEDN) and the IPR Network. We have developed three types of IPR:

- **Source Power Router (SrcPR):** these routers provide an interface between Power Generators (drawn as circles) and IPR Network. They inform other IPR on the status of power generators.

- **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 (SnkPR):** These routers interface between Loads and the IPR Network. Their principal function is to connect and disconnect loads as required.
Each IPR has a set of lines classified as either Input or Output lines. These output and input lines correspond to transmission or distribution lines that move power between the buses associated with each IPR. In the remaining of this proposal, we assume that we are dealing with a transmission system. An input line models a transmission line that brings power into the bus associated with a given IPR. Likewise, output lines model a transmission line (or branch) that feeds from the bus associated with a given IPR. Decisions for the activation of contingency plans from IPR are based on two factors:

**Priority Factor:** Every output line has a priority factor, similar to the priorities assigned to the loads. These priorities indicate which lines must be serviced first, in the event of a contingency.

- **Reliability Factor:** Every input line has a reliability factor, which indicates how reliable is the power source feeding the line.

Several message types are defined for IPR communications and interactions. Their purpose is to maintain each IPR aware of the conditions in its neighboring IPR. These message types are:

- **Steady state messages:** These messages are designed to exchange information between adjacent IPR while the EEDN is in normal operation state.

- **Contingency messages:** When a fault occurs in the EEDN, these message types will be exchanged between IPR during the system restoration process.

**Figure S-10:** Relation between EEDN, IPR location and IPR logical connections.

(Gen n: Generator n, SrcPR: source Power Router, PPR: Principal Power Router, SnkPR: Sink Power Router)

### §4.5 Islanding – Zone Approach via IPR

The key to improve the performance and quality of the IPR decision making resides in their knowledge of the state of their neighbors. Hence, they must exchange state messages continuously. But, as the IPR Network grows, the number of messages
will grow exponentially too, generating congestion in the communications network and making it difficult for IPR to get the status messages necessary to understand current system conditions. To avoid this, we divide the system into zones or geographical regions. Each zone has a balance between capacity for energy generation and demand for consumption. Each zone behaves as an autonomous network of IPR, capable of exchanging messages with other zones, while also been able to possibly contain and repair failures within the zone.

To support this Zone approach we need a second IPR classification scheme. *Interior IPR* are those that exchange messages within a given zone. *Border IPR* exchange messages between different zones. Figure 5-11 shows an example of a Power System divided in two zones (Zone A and Zone B). Zone A has nine buses and each bus has an IPR. Zone A has six interior IPR and three Border IPR. Likewise, Zone B has 10 buses with eight Interior IPR and two border IPR. The operation of each of IPR is as follows:

- **Interiors IPR**: Their main function is to establish a secure operational state in the interior of each Zone. For this reason, each Src-IPR informs the state of its generator in a message that is spread to the interior of the zone. In this way, every other IPR knows the state of generators in its zone, allowing it to modify its reliability table to request power from generators with more probability of responding to its request. This scheme avoids the waste of time and resources in asking for power from generators that cannot satisfy such requests.

- **Border IPR**: When zone X experiences a demand in power that cannot be served by its local generators, the border IPR of that zone request power from their neighboring zones to guarantee that The entirety of the loads in zone X are served, or at least as many as the high-priority loads as possible. In the event of a catastrophic event that forces the partition of the systems in islands, the border IPR in each zone exchange messages to coordinate the re-interconnection process among those islands.

**Figure 5-11: Example of Zone-Island approach**

To simplify the negotiation schema, Border IPR see each neighboring zone as a Generator or as a Load (Network Equivalent) depending on the power flow direction. If power is entering from zone A to zone B, then the borders IPR at zone B see zone A as a
generator. Likewise, the border IPR in zone B see zone A as load. Figure S-1111 illustrates this idea; it shows the view of Zone A for Border IPR of Zone B as two generators and two Loads. These generators are the least reliable generators for Zone B.

S.4.6 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 will have the capacity to improve the state of the system by means of a negotiation in several stages looking to increase the number of loads with high-priority that are served.

Intra-Zone Negotiation

The first phase of IPR negotiation is performed at the intra-zone level. At this stage, the Interior-IPR works to satisfy the maximum number of high-priority loads in the interior of its zone. By means of a periodic exchange of messages, the interior IPR are able 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.

**Friendly Request Stage:** In this stage of the negotiation the IPR follows the normal outline of negotiation described in [23]. In this scheme, each load uses its SnkPR to pose requests for power to the IPR network. Each request is routed until an affirmative answer or negative answer is found, which depends on current system conditions. Following the priorities schema, IPR choose which loads can be served and which cannot. In this phase, the IPR try to return the system to its previous safe operational state, maintaining request direction as the power flow was before the catastrophic event. But, if a high priority load sends a late request and the resources of the system are already committed and they do not allow serving this load, then this high priority load will receive a negative answer. In this first phase, loads of high priority might not be served at all. The second and third phases deal with such situation.

**Persistent Request Stage:** The SnkPRs that receive a negative answer in the Friendly Request stage now send a *Persistent Service Request*. This type of request forces the IPR to attempt a system reconfiguration by changing the direction of the power flows necessary to satisfy most of the high-priority loads. When the request reaches a generator, the associated SrcIPR triggers the schema of load shedding to assure power to the highest priority loads.
Load Shedding Communication Stage: When a SrcPR 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 SrcPR sends a Disconnect Message following the path stored in the message to reach the SnkPRs servicing the low priority loads. The SrcPR then awaits for a Disconnect Confirmation Message. This latter message is routed by the IPR in the path between the SrcPR and the SnkPRs. When the SnkPR gets a Disconnect Message, it disconnects its associated load and sends a confirmation disconnect message to SrcPR that sent the original message. Then, the SnkPR for the load just disconnected starts looking for power from alternative generators. When the SrcPR receives the disconnect message from all targets for disconnection, it sends an affirmative response to the high priority load to be serviced.

Inter-zone Negotiation

The objective of this phase is to bring power from another zone to try to restore the loads that were not served in the Intra-Zone negotiation process due to insufficient generation capacity. When a SnkPR receives a deny response for a Persistent Request Message, it sends an Inter-zone Assistance Request, and this message is routed until it gets to a Border IPR. This Border IPR sends this request to its peer Border IPR in another zone. When a Border IPR receives an Inter-Zone Request, it stores this message and sends a Friendly Request Message to the IPR in its local zone network. Notice that this message is treated as an Intra-Zone message and it is processed as mentioned in the previous section. The idea is to handle the request as if it came from a load inside the zone of the Border IPR.

When the Border IPR receives the final response, it sends that response to the border IPR X in the zone which initiated the negotiation process. If this message is an affirmative response, border IPR X sent this response 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 denial response is obtained from all Border IPR. In this latter case, a final Denied Response is sent to the SnkPR that made the original request. This SnkPR awaits a time interval $T$, and then begins the whole process again.
### §4.7 Experimental Results

In order to demonstrate the effectiveness of the proposed approach, we have implemented a software library with all the protocols and communications for IPR operations as presented before. We are still working on the implementation of the Inter-Zone scheme. Our computer simulation was built using the Java programming language, and it was run on several computers interconnected via a 100Mbps LAN. In [23] we have presented one of the simulation cases with its conditions, which we ran on a modified version of the WSCC nine-bus model. The objective of our simulation was to obtain a reservation and allocation of power resources to enable a system restoration after a total system blackout.

As [23] presents, after running the test cases four times, the power allocation negotiated by IPR can supply 100% of the power required by loads in each case. Moreover, the allocation of power satisfies the constraints established in the mathematical formulation. This was all accomplished in a decentralized manner and using only local information available to each IPR.

### §5 Risk Assessment of a System Operating with IPR

For the purpose of calculating the reliability of an individual IPR we divide the IPR into three sub-systems, namely; power hardware (breakers or other power switching elements), computer hardware (the data router that permits communication between IPR and CPU functions), and software as depicted in Fig. 1. We identify failure modes for each sub-system of the selected IPR structure to estimate the IPR reliability [24]. This estimate of failure probability for an IPR will be used in our work to measure the change in reliability of a power system operated with and without IPR.

#### §5.1 IPR Components

The operational relationship of IPR sub-systems is shown in [Fig. $\text{A-Software}$]. The Intelligence section (i.e. software) consists of the algorithm which will make and execute decisions, while the IPR operates. The intelligence section will control the switching device of the IPR depending on the network status.
B- Power Hardware. The switching device of an IPR can be a high voltage circuit breaker, FACTS (Flexible AC Transmission Systems), or another switching device capable of controlling the power flow in the transmission/distribution lines.

C- Computer Hardware. The data router section will handle the communication between IPR. They have to communicate the status of the network and useful data obtained by the system sensors (PT’s, CT’s, etc.) for the intelligence section to analyze and take appropriate action.

S.5.2 Configuration

Figure S-13 shows possible functional configurations for the internal components of an IPR. Figure S-13(a) shows the basic series configuration. If any of the internal components fail the IPR will fail. We assume that the probability of failure of each component (software, data router, and breaker) is independent of each other. Figure S-13 (b), (c), (d) and (e) introduce a redundant path for the software, router, and software-router respectively. If the main path fails, there is an auxiliary path allowing the IPR to maintain full functionality. We do not provide a redundant path for the breakers because we assume the cost of power breakers to be much higher than that of software or routers.

S.5.3 Example

In [25] Anderson reviews important concepts to be the probability that a component or system is working properly during a given period of time when used under stated operating conditions. These concepts are the basis of our work. Let

\[ R = P \{ \text{successful IPR operation} \} = \text{Reliability} \]
\[ Q = P \{ \text{unsuccessful IPR operation} \} = 1 - R = \text{B} = \{ \text{successful Circuit Breaker operation} \} \]
\[ \bar{B} = \{ \text{unsuccessful Circuit Breaker operation} \} \]

Using the rules for series/parallel systems the following equations are obtained for every configuration shown in Figure S-13:

Conf. (a), \[ R = P(S) P(R) P(B) \tag{S.1} \]
Conf. (b), \[ R = P(S) P(R) P(B) = (1 - P(\bar{S}_a) P(\bar{S}_b)) \times P(R) \times P(B) \tag{S.2} \]
Conf. (c), \[ R = P(S) P(R) P(B) = P(S) \times (1 - P(\bar{R}_a) P(\bar{R}_b)) \times P(B) \tag{S.3} \]
Conf. (d), \[ R = (P(S_a) P(R_{b}) + P(S_a) P(R_{a}) - P(S_a) P(R_{a}) P(S_b) P(R_{b})) \times P(B)) \tag{S.4} \]
Conf. (e), \[ R = P(S) P(R) P(B) = (1 - P(\bar{S}_a) P(\bar{S}_b)) \times (1 - P(\bar{R}_a) P(\bar{R}_b)) \times P(B) \tag{S.5} \]
To complete our example, reliability estimates of each component are needed. From [27] we have that “major failure per breaker year” estimate is 0.00672 for single-pressure high-voltage breakers above 63 kV (all voltages, from years 1988-1991). The reliability of high-voltage breakers can be calculated using the equation \( R(t) = \exp(-\lambda t) \), assuming a constant failure rate [26]. Working with a one year period, the estimate for breakers reliability is \( R(1) = P(B) = 0.99330 \), or 99.330% of confidence.

From [28] we obtain the average MTBF (mean time between failures) of Ethernet routers to be 9.5 years, and for a price multiplier of 25, they are available with 35 years MTBF. From [26] the reliability can be calculated from MTBF indices using the equation \( R(t) = \exp (t/\text{MTBF}) \), again, assuming a constant failure rate. For a one year period, the reliability found is \( R(1) = P(R) = 0.90009 \) for a 9.5-years MTBF, or \( R(1) = P(R) = 0.97183 \) for a 35-years MTBF.

Estimation of software reliability is not an easy task. To make a good estimate we need the total of code lines, loops, the frequency of each loops, the execution time, failure rate, fault density, etc. The software for an IPR is not available, so an estimate of its reliability is not possible. However, we assume a reliability of 0.95 and 0.99 in our example. We believe that these values are conservative, i.e. pessimistic since the controlling software on an IPR will be extremely complex and its decisions will be based on pre-established contingency tables.

Table §1 summarizes the results of reliabilities and failure probabilities for each configuration of Figure §1-13 using their respective equations. As said before, reliability is defined as the probability that a system (component) will function over some time period \( t \), and it can be expressed as \( R(t) = P\{T \geq t\} \), where \( T \) is a random variable of the time to failure of the system. If we define \( F(t) = 1 - R(t) = P\{T < t\} \), then \( F(t) \) is the probability that a failure occurs before time \( t \). The results show, as expected, that non-redundant configurations have lower reliabilities, or higher failure probabilities. Introducing redundancy in at least one of the components, the reliability of the system increases considerably, and reduces the probability of failure. The configurations shown in Figure §1-13 (d) and Figure §1-13 (e) achieved the highest reliabilities.

<table>
<thead>
<tr>
<th>Table §1 Reliabilities and Failure Probabilities of IPR Configurations</th>
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<td>IPR Configuration</td>
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The reliability of the each IPR configuration is lower than the reliability of the breaker alone. We expect these results because the reliability in a series system will be less than the lowest reliability of its components. All our IPR configurations reduce to a series configuration. The only way that the reliability of IPR can be greater than the reliability of the breaker is if we provide a redundant path to the breaker. Does this mean that it is better to have only the breaker instead of the IPR? We believe not. A breaker will act based on local data, without regard...
to the system state outside its protection zone. The IPR, through its communication capabilities, will act based on local and regional data enhancing the system reliability. The classical methods do not capture properly the increase in the reliability of a power system when a special protection scheme (SPS) is included. However, it is known that when a SPS, like an IPR, is properly operating, significantly improves system response following a contingency, and therefore, the system reliability [29]. To capture properly the reliability increase in a power system we will use the Risk Framework Assessment developed by McCalley et. al. [29]. In the following we show a summary of the reliability assessment for a section of the 179 buses system including an IPR. The system will suffer voltage collapse if lines L76-78 and L78-80 simultaneously have an outage. A solution to prevent system collapse is to install VAR compensators in buses 78 and 75. An IPR can be used to activate these compensators in the event that there is one line outage to prevent the collapse in the case that the other line has an outage too.

**Nomenclature**

- \( F_i \): event there is a fault on ckt \( i \) (L76-78, L78-80)
- \( A \): fault type (1Φ, 2Φ, 3Φ, Φ-Φ)
- \( N_C \): # critical circuits
- \( N_T \): total number of events considered in the study
- \( E_i \): initiating events
  - \( N_C \) event \( \rightarrow \) “N-1” outage
  - \( N_{C+1} \) event \( \rightarrow \) No fault
- \( E_{i, i > N_{C+1}} \): simultaneous outage 2 or more circuits
- \( K \): system collapse event

**Risk Sources for a system with IPR**

1. IPR fails to act in a contingency. The system may or not may collapse depending on the pre-fault operating condition.
2. IPR works properly, no collapse, but non zero impact.
3. IPR works unnecessarily when there is no outage. Non-zero impact.
Risk of an event $E_i$, $i = 1, 2, \ldots$ which causes IPR to act or system collapse $K$:

$$Risk(K \cup T) = \sum_{i=1}^{N_T} Risk(E_i) = \sum_{i=1}^{N_T} \Pr(K \cap \overline{T} \cap E_i) \times \Im(T \cap E_i) + \sum_{i=1}^{N_T} \Pr(T \cap E_i) \times \Im(T \cap E_i)$$  \hspace{1cm} (S.6)

where,

$$\Pr(K \cap \overline{T} \cap E_i) = \Pr(\overline{T} \cap E_i) \times \Pr(K \mid (\overline{T} \cap E_i))$$  \hspace{1cm} (S.7)

Each component (R, S, and B) can have two failure modes: 0-working, 1-failure. In this case, the IPR may assume 16 states ($2 \times 2 \times 2 = 2^4 = 16$).

Some states are identical (e.g., 0010 and 0001), so we can merge them. The resulting states are:

$S_0 \rightarrow 0000$
$S_1 \rightarrow 0001, 0010$
$S_2 \rightarrow 0011$
$S_3 \rightarrow 0100$
$S_4 \rightarrow 0101, 0110$
$S_5 \rightarrow 0111$
$S_6 \rightarrow 1000$
$S_7 \rightarrow 1001, 1010$
$S_8 \rightarrow 1011$
$S_9 \rightarrow 1100$
$S_{10} \rightarrow 1101, 1110$
$S_{11} \rightarrow 1111$
Now, we classify the states into categories. There are four possible categories:

- **C1**: There is an active signal (AS, switching event). IPR works properly. If there is an inactive signal (IS, non-switching event) IPR works unnecessarily.
- **C2**: There is an AS. IPR works properly. If there is an IS, IPR does not switch (works properly).
- **C3**: There is an AS. IPR does not work properly. If there is an IS, IPR works unnecessarily.
- **C4**: There is an AS. IPR does not work properly. If there is an IS, IPR does not switch (works properly).

Before we classify each state, we must characterize the failure mode for each component:

- **B → 0**, the breaker switch properly
- **1**, the breaker does not close

- **R → 0**, the router communicates properly
- **1**, the router does not send any information

- **S → 0**, the software works properly
- **1**, the software takes an incorrect decision

Now, the states can be classified in the following manner:
- **C1**: \( S_9 \)
- **C2**: \( S_0 \)
- **C3**: \( S_3, S_4, S_{10} \)
- **C4**: \( S_1, S_2, S_5, S_6, S_7, S_8, S_{11} \)

The resulting Markov chain is shown in Figure $\text{5-15}$, where,

- \( \lambda_1 = \frac{1}{9.5}/365 = 0.10526/365 = 0.000288392 \)
- \( \lambda_2 = 0.05129/365 = 0.00014053 \)
- \( \lambda_3 = 0.00672/365 = 0.0000184110 \)

These values were obtained from the MTBF, MTTF or the annual failure for each component. The failure rate of the router (\( \lambda_1 \)) was obtained from its MTBF of 9.5 years. The daily rate of the software (\( \lambda_2 \)) was calculated from the assumed reliability of 0.95 and converted to the failure rate per year of 0.05129. Finally, the failure rate of the breaker (\( \lambda_3 \)) was obtained from literature.

To find the risk, the conditional probability in equation 7 is needed: \( \Pr(K/(\overline{T} \cap E_j)) \). From simulations, it is known that the probability of collapse given that occurred event \( E_3 \) or \( E_4 \) and there is no tripping action of the IPR is 1 and 0 for \( E_3 \) and \( E_4 \) respectively. However, for events \( E_1 \) and \( E_2 \) the probability is not known. Right now, we are working with a
technique known as Voltage Stability Index to establish a probability function to obtain these probabilities and finalize our risk assessment.

§.6 Distributed Control Models

§.6.1 Distributed Control of Electronic Power Distribution Systems

Today's complex electronic power distribution systems (EPDS) in data centers, automotive, ships and aircrafts require sophisticated control techniques to support all aspects of operation including failures. When a high degree of reliability is desired the effects of failures must be mitigated and control must be maintained at survivable scenarios. In order to manage fault scenarios, we need to make a series of decisions and control actions:
1. The fault has to be detected,
2. The fault source has to be identified and its magnitude estimated (partial degradation vs. total failure),
3. Depending on the nature of the failure, a new control algorithm has to be selected that compensates for the failure,
4. The EPDS has to be reconfigured, and
5. The new control algorithm has to be chosen.

All these decisions must be made by a control system that incorporates not only simple regulatory loops and the supervisory control logic, but also a set of components that detect, isolate, and manage faults, in coordination with the control functions. A block diagram for a self-reconfigurable control system is shown in Figure §-16.

![Figure §-16: A Self-reconfigurable Control System](image)

Hybrid dynamical systems theory offers a natural framework to deal with the modeling and fault adaptive control problems in EPDS. Considerable research work has been dedicated to the study of various aspects of hybrid systems including modeling, stability analysis and control. Intelligence in the context of hybrid dynamic systems refers to the capability of these systems to adapt and reconfigure themselves to significant changes in their operating environment and their own structure. An example of a self-reconfigurable control system is the fault adaptive control system described in [30]. Fault adaptive control systems in particular have been studied in the context of robotics [31] and manufacturing automation [32].
In general, autonomous systems are seen as one of the most important trends in control systems. Autonomous systems are becoming an important change of paradigm in the control of AC power systems [33][34] similar trends are being investigated for EPDS in ships [35], automotive [36], and space applications.

Our research work is focused on studying different approaches to realize a self-reconfigurable control system for EPDS.

**S.6.2 Ship Integrated Power System**

Integrated Power System (IPS) is the term applied to a ship architecture where both ship service loads and ship propulsion are supplied from a common electrical source. In the IPS concept proposed by the Advanced Surface Machinery Program of the NAVY Naval Sea Systems Command, the power distribution is based on the zonal distribution architecture, which includes both AC backbone and DC zonal systems. Zonal architectures have several advantages over traditional ring bus distribution systems supplying radial feeders, including better reconfigurability and greater survivability [37]. Compared to radial distribution, zonal distribution architectures provide maximum protection (fault tolerance), reduced cabling, and cost savings.

A diagram of the ONR reference IPS provided for self-reconfigurable control system studies is shown in Figure 1. This system contains the minimum elements to represent an advanced IPS [35]. System characteristics include:

1. Two finite inertia AC sources and buses
2. AC bus dynamics, stability and regulation
3. Redundant DC power supplies and zonal distribution buses
4. DC bus dynamics, stability and regulation
5. Three zonal distribution zones feed by redundant DC power buses
6. A variety of dynamic and nonlinear loads

An actual ship would typically have five to eight zones instead of three as shown in Figure 2.
S.6.3 DC Zonal Electric Distribution System

Simulation will be our primary tool to test and validate the control algorithms to be developed in this work. In our initial stages, we are using the Simulink™ implementation of the DC Zonal Electric Distribution System (DCZEDS) described in [35][37][38] which is a simulation testbed for control algorithms for ship power distribution system provided by the Office of Naval Research (ONR) to researchers in the NSF/ONR Electric Power Networks Efficiency and Security (EPNES) program [35].

Figure S-18 shows an expanded version of the DCZEDS in Figure.

![DC Zonal Electric Distribution System Diagram]

**Figure S-18: ONR IPS Reference System DC Zonal Distribution System.**

![SIMULINK DCZEDS Simulation Results graphs]

**Figure S-19: SIMULINK DCZEDS Simulation Results**
The reference DCZEDS is fed by two 500-V busses; one on the Starboard side and one on the port side. Each bus is connected to an electrical zone through a Ship Service Converter Module (SSCM) that serves to buffer the main bus and the intra-zone electrical loads and to provide a voltage level appropriate to the load. Diode networks are used for automatic bus transfer. AC loads are fed by Ship Service Inverter Module (SSIM). In addition to power conversion functions, the SSCM and the SSIM provide monitoring and protection functions.

The DCZEDS consists of two power supplies (PS's), six Ship Service Converter Modules (SSCM's), three diode networks, one Ship Service Inverter Module (SSIM) with an associated load bank (LB), one motor controller (MC), and one Constant Power Load (CPL). The loads are divided into three zones as shown in Figure $\text{S-18}$ All DCZEDS subsystems and modules have local controllers.

The components and subsystems of the DCZEDS have local conventional controllers. Our goal is to add to this system the fault detection and reconfiguration logic to develop a self-reconfigurable power distribution system.

Some Simulation Results

Simulation studies using the DCZEDS model are being performed to understand how it functions and its limitations. Normal operation and fault scenarios are being evaluated. Figure $\text{S-19}(a)$ shows results of a system startup simulation. As expected, under no faults, the system reaches steady state with no major problems. Examples of potential faults are:

1. Isolated faults at the individual zonal loads
2. Faults at the distribution buses
3. AC propulsion bus fault (i.e. generator fault)

Figure $\text{S-19}(b)$ shows simulation results when there is a fault in the Port distribution bus. As expected the system can supply power to all loads from the Starboard bus. A defect in the SIMULINK model is that loads are only connected through the corresponding SSCM to either the starboard or the port bus which results in a limited number of potential faults and reconfiguration possibilities. An enhanced implementation of the DCZEDS system of Figure $\text{S-18}$ has been implemented in the Virtual Testbed (VTB) Environment and presented in [39]. We have obtained a copy of this model from Dr. Roger Dougal from University of South Carolina. We are also enhancing the SIMULINK model by including topological rules to limit the number of loads that can be connected to a bus and adding priorities to the system loads to include load shedding in the reconfiguration schemes.

\textbf{S.6.4 Implementation of the Reconfiguration Logic}

We selected MATLAB™ SIMULINK™ together with MATLAB™ Stateflow™ Toolbox to conduct the simulation experiments and implement the reconfiguration logic. Stateflow is a graphical tool that works with Simulink. Stateflow lets you design and develop deterministic, supervisory control systems in a graphical environment. This
program visually models and simulates complex reactive control to provide clear, concise descriptions of complex system behavior using finite state machine theory.

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<thead>
<tr>
<th>G1</th>
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Figure S-20: System Truth Table for distribution bus faults.

A finite State machine diagram can be used to represent new system configuration. Figure $-$ shows a truth table for the modes for the system and Figure S-21: shows a finite state transition diagram for the DCZEDS when a distribution bus fails.

Figure S-21: System operating modes for the distribution bus fault example.

Current works continues the simulation studies and we are looking at different methodologies to design the logic control component of the supervisory system.

S.6.5 Conclusion

The future of power systems for ships will be based on zonal architectures making them an ideal testbed where to evaluate potential concepts for self-reconfigurable systems for electronic power distribution systems.

We have finished our evaluation of the DCZEDS as a potential simulation testbed and seem adequate to meet our demonstration objectives. Future work will be focused on the failure analysis and reconfiguration logic of the self reconfigurable system using centralized as well as IPR distributed approach.
Reconfiguration

We have selected to use the Power System Restoration (PSR) problem, an extreme condition in a power system, as a starting point to address the system reconfiguration problem. We are currently using the PSR problem global (centralized) solution as a benchmark against solutions obtained using the IPR approach.

The goal in the PSR problem is to rebuild a stable electric system and restore all unserved loads. Our restoration approach requires that at each stage of the restoration process the values for the control variables that minimize the unserved loads while satisfying the network operating constraints be obtained. The electric power system restoration problem was formulated as a multi-objective, multi-stage, combinatorial, nonlinear, constrained optimization problem and a hybrid discrete and continuous particle swarm optimization (PSO) algorithm was implemented in order to handle the binary and continuous variables of the problem. The proposed method was tested on the well-known 9-bus WSCC equivalent system. The results obtained show the effectiveness and applicability of the proposed method [20].

We are currently developing a controlled islanding mechanism which will permit partial system preservation and rapid system recovery using IPR. The controlled islanding scheme will consider the inherent structural characteristics of the system, as well as the imbalance between generation and load. After the islands are created, appropriate control actions (such as under-frequency and/or under-voltage load shedding) will be executed in order to bring each island to a normal operating state. That way, the extent and duration of a potentially catastrophic event can be effectively limited. The first step in the proposed approach will be to carry out a series of transient stability studies, which will provide valuable information regarding the coherent groups of generators, the quantities that should be monitored to assess the vulnerability of the power system with respect to possible cascading events, and the proper location of the IPR throughout the system.

Economics Issues of the Intelligent Power Router Service

In this section we propose to define the IPR function as an Ancillary Service. To put this in context we discuss the application of the IPR concept in an actual market structure, such as the Standard Market Design (SMD), analyzing a Locational Marginal Price (LMP) implementation.

The Standard Market Design (SMD) Environment

From an institutional point of view, the Federal Energy Regulatory Commission (FERC) has a strong commitment to establish a generalized Standard Market Design (SMD) for the wholesale of electric power in the United States. This process will amount to a post-deregulation effort calling for a new framework of standard guidelines, including the formation of Regional Transmission Organizations (RTOs). The SMD proposal has taken into consideration both the U.S. and worldwide experiences and is intended is to improve the efficiency of the electricity marketplace.
A key of the model is found in the Locational Marginal Price (LMP) feature. This concept is relevant to the notion of intelligent power routers, in particular its local nature which parallels the one for IPR. The LMP can be simply defined as the cost to serve the next MW of load at a specific location, using the lowest production cost of all available generation, while observing all transmission limits. It has three major components, namely generation marginal cost plus transmission congestion costs plus the cost of marginal losses.

The marginal cost to provide energy at a specific location depends on: marginal cost to operate generation, total load (demand) and cost of delivery on transmission system.

It is also significant to mention that this pricing system internalizes the cost of system reconfiguration, plus the transaction curtailments and the re-dispatch of generation in order to serve the next MW of load. All components have a definite bearing upon the IPR concept and leads to the conclusion of this section.

What is somewhat still missing is the load marginal-benefit component of LMP, except for some markets where load bidding is allowed and significant; for these hubs the price reflects rather well the marginal value of electricity from both supply and demand standpoints.

§.9.2 The Ancillary Service (A/S) Context

The A/S is a new essential concept/component of the modern power system. It is a consequence of the unbundling process taking place in the industry. In this context different products and services can be evaluated and priced separately from its original integrated matrix core. FERC defines A/S as those services that are necessary to support the transmission of Capacity and Energy from resources to loads, while maintaining reliable operation of the provider’s Transmission System in accordance with good Utility Practice. From this definition it is clear that the IPR function has a distinct potential to fall into the category of an Ancillary Service.

§.9.3 Reliability Aspects of Ancillary Services

A first insight into reliability stems from the very definition of A/S as previously stated. But good utility practice in the new era is somewhat undefined (in fact the very definition of utility has become a debatable matter in the new world) because of the complexity of the new deregulated environment, the fragmentation of the industry and the difficulty of setting the responsibilities, cost and benefits of security. Examples of relevant services as it relates to security can be found in [21].

§.9.4 The IPR Technical/Social/Economical Potential for Optimality

It is clear that the future electricity networks of the world will operate within some sort of market structure in a deregulated environment, most likely of the SMD type. Certainly this seems to be the trend both in North America and Europe. Therefore the LMP key feature will prevail for the pricing of electricity; this system will be topologically
comprised of either zones or nodes to which such pricing will be referred to. Of course such LMP will eventually evolve from its current basis to a more comprehensive one capable of synthesizing and impounding all the relevant technical/social/economical information with a quasi-real time frequency (price minimum update-cycle time).

Furthermore the classical competitive model sets a random phenomenon capable of sustaining a sort of convolution between supply and demand stimuli. This basically amounts to the negotiating mobility between the players in order to improve their bargaining positions. The process becomes an exhaustive optimization one, whether it applies to a pool or bilateral market framework; the attending outcome which, as well known, tends to clear a price that maximizes the efficiency and social welfare.

There are important parallels between the LMP and IPR fundamentals; this is a most favorable situation. First, regarding the power grid context both are basically local/zonal in nature; actually the very denomination of LMP makes a specific reference of this condition. Second, within the IPR operating principles it has been discussed that there is a sort of an active negotiation between IPR, especially in order to act upon any disturbing event. Through this process, reasonably assumed exhaustive, the router intelligence seeks to establish a grid reconfiguration, ideally retaining/upgrading able generation serving preferred loads in a stable post-disturbance environment. This IPR competitive negotiation resembles and compares favorably with the one taking place between the players of the energy marketplace. It may be considered an extension of it.

But beyond this important observational equivalency there is a potential synergy between the two processes. For the local power router intelligence has also full access to the zonal/nodal LMP. That bit of information can be processed in the IPR algorithm as a part of its negotiating position. As stated below, that price theoretically impounds all the relevant updated information associated to the best rational use of energy the network is serving; actually reflecting the global/zonal marginal value of electricity for the period under scrutiny. Consequently these processes are bound to have an outcome of social optimality.

### §9.5 Proposed definition for the Intelligent Power Router Ancillary Service

Power Routing Ancillary Service - *Functionality provided by distributed Intelligent Power Routers (IPR) whereby network security and efficiency are rendered by performing, under contingencies, timely switching of power apparatus and lines, shed load based on a priority scheme, activate auxiliary or distributed generation, isolate power region of the energy delivery network to prevent system cascade failures and receive/broadcast local state variable information to and from other routers.*

### §9.6 Summary

We can conclude that the IPR may provide improved efficiency and security in the context of a realistic market structure such as the Standard Market Design, with LMP pricing algorithm. This economic model relates to IPR functionality since the routing function may be defined as an Ancillary Service. A definite area for further work can be found on the market mechanism and pricing of such a service.
§.10 Conclusions

We commenced the design and test of architecture for the IPR by developing a model of computer controllable bus that serves as the Energy Flow Control and Sensing Device of the IPR. Furthermore, the IPR are organized in a peer-to-peer (P2P) communication network that exchange state messages continuously. To avoid congestion in the communications network we divide the system into zones, each zone an autonomous network of IPR, of balanced generation capacity and demand. Each zone behaves as an, capable of exchanging messages with other zones, while also been able to possibly contain and repair failures within the zone. IPR are then classified as Interior IPR, those that exchange messages within a given zone and Border IPR, those that exchange messages between different zones. Using a two-stage inter/intra zone negotiation scheme we restore power to high priority loads after a contingency using a de-centralized approach with local information available to each IPR only.

Also, we have estimated the reliability of an Intelligent Power Router (IPR) based on the failure probabilities of its primary subsystems; software, communications and switching element, and a variety of possible functional relationship between these subsystems. Since an IPR has not being built yet we have estimated the failure probabilities of its subsystems from our knowledge of existing similar systems, e.g. existing software, data routers and circuit breakers reliability estimates. As expected, the configurations that provide redundancy achieved the highest reliabilities and lowest failure probabilities. To properly capture the reliability increase in a power system using an IPR we are using the Risk Framework Assessment Approach.

The zonal approach used for civilian power systems is also used for naval ships. We use the Navy DCZEDS test bed to evaluate concepts of self-reconfigurable systems for electronic power distribution systems. Future work will be focused on failure analysis and reconfiguration logic of the self reconfigurable system using centralized as well as the IPR distributed approach.

To complement and expand our successful IPR de-centralized restoration scheme implemented we are currently developing a controlled islanding mechanism which will permit partial system preservation and rapid system recovery also using IPR. The controlled islanding scheme will consider the inherent structural characteristics of the system, as well as the imbalance between generation and load.

We have also explored the possibility of providing improved efficiency and security using IPR in the context of a realistic market structure such as the Standard Market Design, with LMP pricing algorithm. Within this economic model relates the routing function may be defined as an Ancillary Service. Further work can be done on the market mechanism and pricing of such a service.
$.11 Acknowledgements

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$.12 Bibliography


