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IPRs: A DECENTRALIZED FRAMEWORK FOR CONTROLLING ELECTRICAL ENERGY DELIVERY NETWORKS

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Abstract

We have developed a decentralized framework to help control and manage an Electrical Energy Delivery Network (EEDN). Our scheme is based on the idea of modeling the EEDN as a data network, where power generators serve energy to cities, factories, etc. The paths taking the flows of power are then controlled by devices that we call Intelligent Power Routers (IPRs). A new IPRs model is presented in this paper as an improvement of our previous work. These new IPRS maintain the same concept for the next generation power network based on a distributed concept with scalable coordination as in previous. The control protocols and decision algorithms are based on the reliability factor for inputs lines and priority factor for input lines. Also, we add intra-zone negotiation phase and inter-zone phase as a new characteristic to improve IPRs performance, scalability and quality of decisions. Moreover, we present a second prototype of IPRs network with improved performance for system restoration using the new approach.

Key Words
Intelligent Power Routers, Decentralized Restoration, Data Networks, Modernization of Power Grid

1. Introduction

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 (controls centers) managing mission-critical tasks for power generation and delivery [3]. The question that must be raised here is: *what would happen if the control center is also affected by the event causing the failure in the electric network*? 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 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.

As we presented in [3], at the University of Puerto Rico, Mayaguez, 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). 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 activate alternate lines to move power from producers to consumers. This approach borrows from computer networks: a flow of data that needs to be established between two geographically distant end-points is implemented via data routers and forwarding protocols [4]. 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 shall 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 IPRs will make local decisions and coordinate the restoration process with other routers to bring the system, or part of it, back into an operational state. But, the proposed scheme will not substitute current control protocols if there are no major 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.

In the approach outlined previously it is obvious the necessity of a robust protocol for distributed control to coordinate all tasks of IPRs network; in [3] we presented basics aspects associated with distributed control of IPRs and a first prototype version of IPRS. In addition, we analyzed their performance behavior in a simulation scenario. In this paper we present new aspects and results of our research and developments of IPRS. First, we present a brief review of the basic aspects of IPRS, including our mathematical formulation. Second, we present our revised design for the IPR architecture and distributed control protocols. As our third issue, we present our island-zone approach. New Algorithms for intra-zone and inter-zone negotiation are presented as fourth issue. As fifth issue, we present our experimental scenario and results obtained based on our new algorithms. Finally, we present a summary with the most relevant aspects of this paper.

2. IPRS Basic aspects

In this section we present an overview of the basics aspects of the IPRS as presented in our previous paper [3].

2.1 EEDN as a WAN

A Wide Area Network (WAN) is a computer network formed by a set the elements that can move data over geographically distant nodes [5]. The main idea of our approach is to view an EDDN as a WAN. In [3] we presented the similarities between EEDN Elements and Computer Network Elements. The roles of the WAN components are as follows:

- *Data Server*: These elements are in charge of supplying the data to clients.
- *Data Clients*: These elements are the final data consumers, such as common people connected to Internet.
- *Data Links*: They are in charge of transferring data from data servers to data clients.
- *Data Routers*: They are a set of internal nodes where the data links are connected.

2.1.1 WAN Operation

When a Data Client sends an information request to a data server, this server fragments the data in packets and they are sent to the client across the network. The packets are the basic unit of data that can be transmitted over a computer network [5]. 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).

If any router or link of the system fails, the routers typically re-configure the paths to route the packets, and the clients are not affected by such failure. 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.

2.2 Mathematical Formulation

Our mathematical model is a modification of a mathematical formulation presented in [2]. The objective of the mathematical model of our power system restoration approach is to **maximize the number of restored loads that have highest priorities**. Our objective function is given by the following mathematical expression:

$$MAX\sum_{k\in R} L_k * y_k * (\alpha - \mathrm{Pr}_k)$$

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), 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 no restored), and R defines the set of de-energized loads.

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

- Limits on power source available in each bus for restoration.
- Power balance of the system between supply and demand.
- Limits in line capacity for power transmission.

2.3 IPRs Network Architecture

The IPRs are organized in a peer-to-peer network. In this architecture, for a given IPR, it is irrelevant whether its inputs come directly from power producers or other IPRs. 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 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. For this purpose, we put an IPR in each bus of the system. Figure 1 Shows relation between EEDN and IPRs Network.

2.3.1 Types of IPRs

We have developed three types of IPRs[4]:

- *Source Power Router (SrcPR)*: these routers provide an Interface between Power Generators and IPRs Network. They inform 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 IPR Network. Their principal function is to connect and disconnect loads as required.

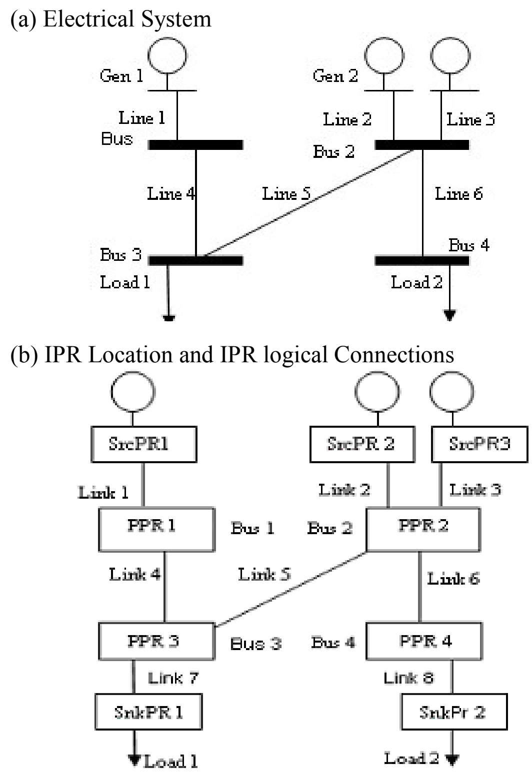

Figure 1. Relation between EEDN, IPRs location and IPR logical connections. (Gen n: Generator n, SrcPR: source Power Router, PPR: Principal Power Router, SnkPR: Sink Power Router) [Referencia]

2.3.2. Decision Factors for IPRs Operations

Each IPR has a set of lines classified as Input and Output lines. These output and input lines correspond to transmission or transmission lines that move power between the buses associated with each IPRs[4]. In the rest of this paper, we assume we are dealing with a transmission system. An input line models 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. Decisions for the activation of contingency plans from IPRs are based on two factors:

- Priority Factor: Every output line has a priority factor, similar to the priority values assigned to the loads. These priority factors 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 source of power feeding the line.

2.3.3 IPRs Message types

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

- Steady state messages: These messages are designed to exchange information between adjacent IPRs while the EEDN is in normal state operation.
- Contingency messages: When a fault occurs in the EEDN, these message types will be exchanged between IPRs during the system restoration process.

3. 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 exponentially too, generating congestion in the communications network [5]. 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 networks of IPRs, capable of exchanging messages with other zones.

3.1 Zone IPRS types

To support this Zone approach we need a new IPR classification. Interior IPRs are those that exchange messages within a zone. Border IPRs exchange messages between zones. Figure 2 shows an example of a Power System divided in two zones (A and B). Zone A has nine buses and on each bus has an IPR. Zone A has six interior IPRS and three Border IPRs. Likewise, Zone B has 10 buses with eight Interior IPRs and two border IPRs.

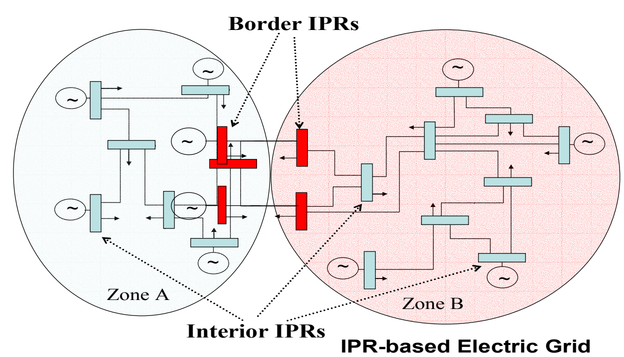

Figure 2. Example of Zone-Island approach

Interiors IPRs. They exchange Intra-zone messages. Their main function is to establish a secure operational state to the interior of each Zone. For this, each Src-IPR 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 to 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 among zones, to maintain the general state of the system. When in a zone, there is a demand that can not be served by its generators, the border IPRs request power to their neighboring zones to guarantee the entirety of the loads in zone 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.

3.2 Zones as Power Network Equivalents

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 2 illustrates this idea; it shows the view of Zone A for Border IPRs of Zone B as two Generators and two Loads. These Generator are the least reliable generators for Zone B.

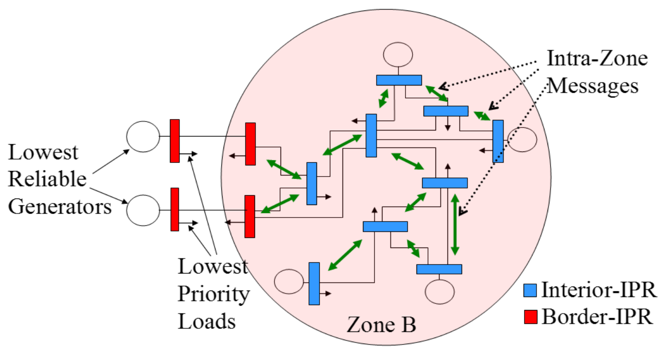

Figure 2. Interior and Border IPRs

4. 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 state of the system by means of a negotiation in several stages looking for whenever the loads of more priority are served.

4.1 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 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 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 negotiation intra-zone is carried out in three stages, discussed below.

Friendly Request stage. In this stage of the negotiation the IPRs follow the normal outline of negotiation described in [3]. 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 schema, IPRs choose which loads can be served and which not. In this phase the IPRs try to return the system to its previous operational State, maintaining request direction as 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 assigned and they do not allow serving this load, this load will receive a negative answer. In this phase loads of high priority they can be un-served. Or, if the previous power flow directions prevents that a high priority load is served, this it was without attendance.

Persistent Request 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. 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 schema. 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 waits for a Disconnect Confirmation Message. This latter is routed by the IPRs in the path between the SrcPR and the SnkPRs. When the SnkPR gets a Disconnect message, it disconnects its load and send a confirmation disconnect message to SrcPR that sent the 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.

4.2 Inter-zone Negotiation

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 denial response is obtained from all Border IPRs. In this latter case, a final Denied 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.

5. Experimental Results

In order to validate our new approach, we have implemented a new software library with all the protocols and communications for IPRs operations and the algorithm presented above. This simulation was built using the Java programming language, and it was run on several computers interconnected via a 100Mbps LAN. Each IPR ran as an independent Java program, and we ran each IPR on a different computer on the network.

The objective of our simulation consists in obtaining a reservation and allocation of power resources to enable a system restoration using the new IPRs approach after a total system blackout. Thus, the IPRs will negotiate to find out an efficient (but perhaps sub-optimal) allocation of power to each line and loads.

5.1 Simulation Scenarios

Our test system is a modification of the WSCC nine-bus model**.** The model used consists of a network of three generators, nine buses and three loads as depicted in figure 3, every system components are organized in only one zone, so every negotiation will be in the intra-zone phase. We use several scenarios, but in this paper we present two of these scenarios, being the second scenario a modification of first. We shall present Inter-zone scenarios in a future paper.

5.1.1 First Scenario – Solve in one stage

In the main simulation scenario the lines 2-8 and 4-1 are not available islanding generators 1 and 2 (see Figure 3). Table 1 shows the values of the principal variables to our simulation.

Table 1. Conditions of Simulation First Scenario

Bus	Line	Limit	Reliability	Priority
1	Gen 1	250 MVA	1	/
	1 – 4	250 MVA	/	1
2	Gen 2	300 MW	1	/
	2 – 8	300 MVA	/	1
3	Gen 3	270 MVA	1	/
	3 – 6	270 MVA	/	1
4	4 – 1	250 MW	1	/
	4 – 9	250 MVA	2	2
	4 – 5	250 MVA	3	1
9	4 – 9	250 MVA	2	3
	9 – 8	250 MVA	1	2
	Load 1	125 MW	/	1
8	8 – 2	300 MW	1	/
	9 – 8	250 MVA	2	2
	8 – 7	250 MVA	3	1
7	8 – 7	250 MVA	2	3
	7 – 6	150 MVA	1	2
	Load 2	100 MW	/	1
6	6 – 3	270 MW	1	/
	7 – 6	150 MVA	2	1
	6 – 5	150 MVA	3	2
5	6 – 5	150 MVA	2	2
	4 – 5	250 MVA	1	3
	Load 3	90 MW	/	1

Results

After running the first test cases five times, the power allocation negotiated by IPRs can supply the highest priority loads in each case (Loads 2 and 3). Moreover, the allocation of power satisfies the constraints. This result is obtained after the first negotiation stage of intra-zone negotiation (**Friendly Request stage)**. The Figure 3 depicts final system status.

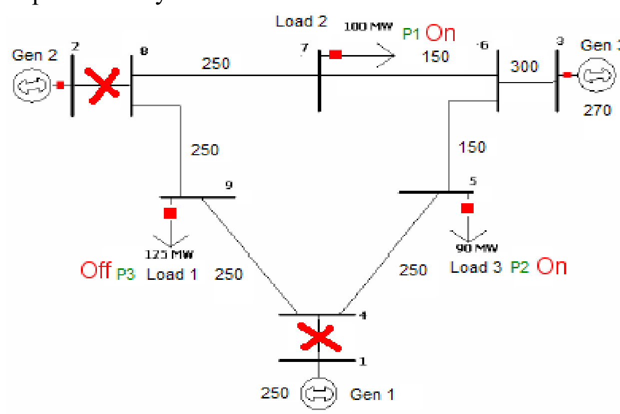

Figure 3. Final results

5.1.2 Second Scenario – Solve in two stages

In the second scenario we changed loads priority values between Load 1 and Load 3, now Load 1 is priority 2 and load 3 has priority 3 (see Figure 4).

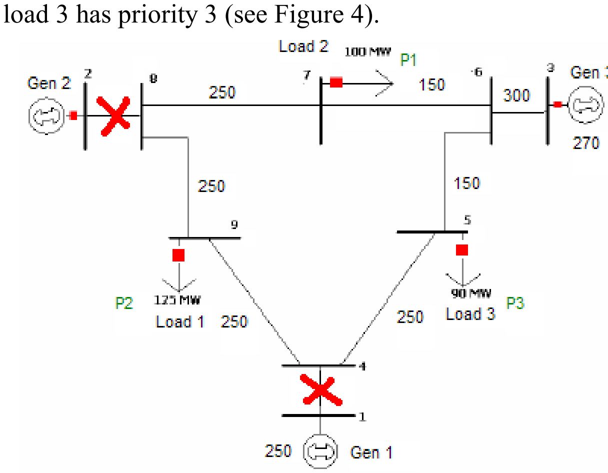

Figure 4. Conditions for second scenario.

Results

To comply with our objective function in this scenario, our IPRS prototype must make two stage Intra-zone negotiation process, because in the first stage we obtained power for Load 2 (priority 1) and Load 3 (priority 3), and Load 1 (Priority 2) did not get power allocated. In this case, the request message of load 1 is sent to bus 9 and this responds with a denied message, this message is received by bus 9 and it sends a request message to bus 4; bus 4 respond with a denied message to bus 9, and the message is sent to load 1. While this occurs, load 2 and load 3 get power for themselves. Figure 5 shows the results of this first negotiation stage.

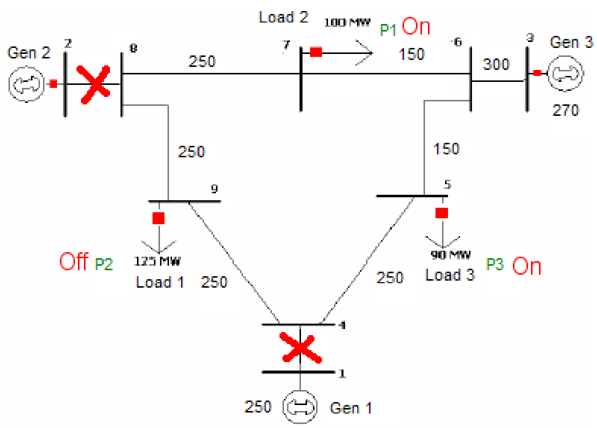

Figure 5. Results of first negotiation stage

Second negotiation stage

After Load 1 receives a denied message, it sends a *Persistent Service Request*; this message is routed across the IPRs Network until it reaches Gen 3. This Generator process the request checking its service table and it find a less priority load served, namely Load 3. Gen 3 sends a Disconnect Message to Load 3, and then it wait for a Disconnect Confirmation. After Gen 3 receives this message, it sends an Affirmative Response to Load 1. After the second negotiation stage, we obtain Load 1 and Load 2 served, and Load 3 disconnected. Figure 6 shows this new system conditions.

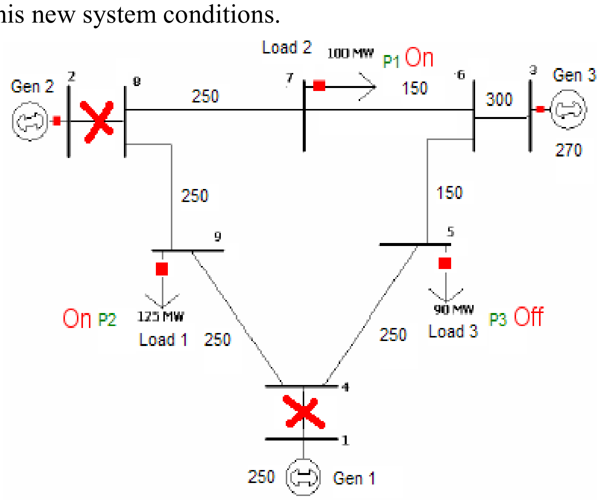

Figure 6. Results in second negotiation stage

6. Summary

A new IPRS model was presented in this paper as an improvement of our previous work. These new IPRS maintain the same concept for the next generation power network based on a distributed concept with scalable coordination as in previous. The control protocols and decision algorithms are based on the reliability factor for inputs lines and priority factor for input lines. Also, we added intra-zone negotiation phase and inter-zone phase as a new characteristic to improve IPRs performance, scalability and quality of decisions. Moreover, we have presented a second prototype of IPRs network that has a satisfactory performance for system restoration using the new approach.

We are working to test the new approach with the WCSS 179-bus system. After that, the next step of this research is oriented to involve new power systems characteristics such as Reactive Power, system frequency and system voltage.

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