Contingency-Based Nodal Market Operation Using Intelligent Economic Alarm Processor

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***Abstract*—This paper focuses on system monitoring and alarm processing and the use of those alarms for economic decision in the nodal electricity market. The task of an Intelligent Economic Alarm Processor (IEAP) is to analyze thousands of alarm messages and extract useful information that explains cause-effect sequences associated with the unexpected contingencies. A graphical Fuzzy Reasoning Petri-nets (FRPN) model that uses fuzzy logic parameters to effectively tackle the uncertainties is built. The economic alarm processor module then processes the fault event signal, analyzes the impact on the market operation activities and different participants, and gives recommendations to optimize the total economic impact under fault scenarios. A contingency-based strategic bidding model concept is proposed to help the market participants take advantages of the latest system operation information and maximize their benefits over the competitors.**

***Index Terms*—Alarm processing, electricity market, fuzzy reasoning Petri-nets (FRPN), intelligent economic alarm processor (IEAP), strategic bidding.**

I. Introduction

TRANSITIONS from the zonal based market system to a nodal based market system are happening in the U.S. regions, like California ISO and ERCOT etc. [1]. The transition brings more complexities in the system operation and electricity market as there is larger amount of data and more price signals, as shown in Fig. 1 [2]. It also has placed great emphasis on the availability of the grid information, the analysis of this information, and the subsequent decision-making to optimize system operation in a competitive environment.

This creates an urgent need for better ways of correlating the market activity with the physical grid operating states in real time and sharing such information among market participants. Choices of command and control actions may result in different financial consequences for market participants and severely impact their profits. Because of this, new solutions have to be implemented toward integrating grid control and market operations taking into account both good engineering practices and appropriate economic incentives.

A lot of studies have been done to illustrate the relationship between physical system operations and market activities from different aspects. Reference [3] describes the interface and persistent gap between market and system operations in restructured electricity markets along with some lessoned learned through the restructuring experience in the United States and abroad. References [4], [5] discusses how the market risks in operations can be measured and those risks may be managed in both operational and financial ways. Models have been proposed to demonstrate the financial effects of power purchase based on probability and consequences. The work in [6] analyzes the impacts of emergency events on day-ahead and real-time market LMPs. The concept of "economic alarm" was first raised in [7] to augment conventional electrical alarms and to bring to the attention of transmission system operators and market participants changes in system operating and economic conditions in an electric power system. The authors ranked the alarm based on the economic severity, and a set of predetermined events that would give certain suppliers the ability to exercise market power will trigger an alarm.

Alarm processing has been a traditional feature of the electricity grid energy management system and has been studied extensively over the past decades [8]–[11]. The solution of Intelligent Economic Alarm Processor (IEAP) proposed in this paper firstly gives a list of the fault occurrence possibilities based on the Supervisory Control and Data Acquisition (SCADA)/Intelligent Electronic Device (IED) signals the system processes using a Fuzzy Reasoning Petri-Nets (FRPN) model [12]. Following these events, changes in power flows, LMPs and other indices are calculated and analyzed. A closer cause-effect relationship

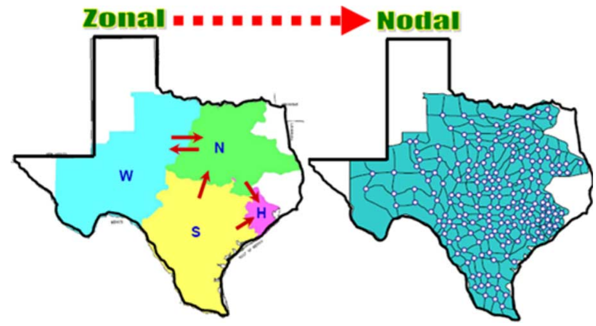
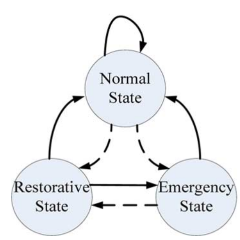


Fig. 1. Transition in Texas.



Type	Configuration	Market Parameters
Normal	All MPs complete	Within Limits
Emergency	All MPs complete	Parameter(s) violate the limits
Restorative	Structure incomplete	Within limits

***MPs(Market Participants)**

Fig. 2. System and market operating states.

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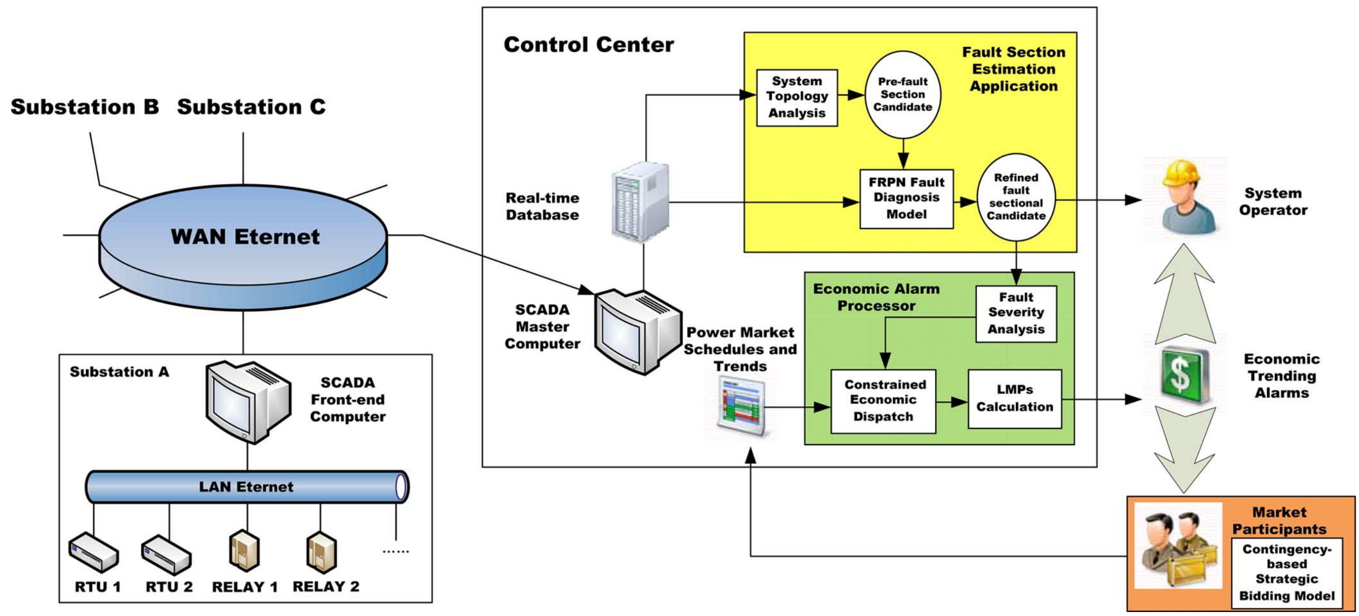


Fig. 3. Intelligent economic alarm processor structure.

between the physical electricity grid and the market is provided [13]. Both physical and economic alarms are filtered and translated into easy-to-understand and real-time information. The paper first gives a brief background of the relationship between electricity grids and markets. The intelligent economic alarm processor as defined by the authors is explained afterwards. The fault section estimation and economic alarm processor module are discussed next. A case study how the two models may be utilized is given with a proposed concept of the contingency-base bidding model mentioned at the end.

II. Electricity Market Architecture and Grid/Market Relationship

The independent system operator (ISO) maintains the instantaneous power balance in the system [14]. Its basic responsibilities include monitoring system security functions and re-dispatching generation as necessary to eliminate real-time transmission congestion and maintain system reliability. This includes taking all necessary emergency actions to maintain the system security in both normal and abnormal operating conditions.

In order to establish an effective real-time monitoring and control system for integrated grid and market operations, the relationship between the two needs to be examined. The market structure for scheduling electricity includes forward bilateral contracts and centrally coordinated markets for day ahead, hour ahead and real-time energy and ancillary services. Once the forward markets have closed, the real time market operation coincides with real time system operations. Schedules from the forward markets are implemented in the real time dispatch and resources made available through the markets to provide ancillary services are selected and dispatched by the system operator for balancing and regulation.

When some operating parameters, such as voltage/current, exceed acceptable limits, the system shifts spontaneously (dotted line in Fig. 2) to an unstable "Emergency" state. The result is usually an automatic control action (solid line in Fig. 2), such as the tripping of a relay, which takes the system into a more stable but not fully functional "Restorative" state. Analogous states and transitions are also applicable in electricity markets, with some notable differences, as shown in Fig. 2.

Based on the assumption that the system reliability is not immediately threatened when certain fault event occurs in the system, our proposed IEAP model will give operators and other market participants advance notice of an imminent need to serve scheduled loads, find replacement for the transmission transfer capacity, or meet services need.

III. Intelligent Economic Alarm Processor Model

The Intelligent Economic Alarm Processor (IEAP) can be implemented in a control center to assist the grid operator in rapidly identifying faulted sections and market operation management. The structure of the application as well as its SCADA support infrastructure is illustrated in Fig. 3.

The IEAP application mainly includes two modules, Fault Section Estimation Application and Economic Alarm Processor.

In such a solution, input data such as relay trip signals and circuit breaker status signals are acquired by RTUs of the SCADA system. In the control center, the SCADA master computer puts the input data into a real-time database and keeps updating them at each scan time.

The IEAP application includes two modules, Fault Section Estimation Application and Economic Alarm Processor. In the first module, the Fuzzy Reasoning Petri-net (FRPN) diagnosis model and data in the real-time database corresponding to each section in the rough candidate set are used. Each section is associated with a truth degree value (the possibility of fault occurrence). The section with a truth degree value greater than a certain threshold is included in the refined fault candidate set.

Such a refined fault candidate set is presented to the system operator for decision-making.

In the second module, the processor firstly analyzes the fault severity based on the information retrieved from the fault section estimation module, and gives the changes in the LMPs, total generation cost, congestion revenue etc. with electricity market schedules and trends. Then some suggested restorative actions are given to optimize the overall system benefit.

When market participants receive the system and market data in advance, they make estimation about the system operator's restorative action and their competitors' reaction to it. The contingency-based strategic bidding model assumes that all the suppliers' and consumers' bids follow a linear function, and will adjust the bidding coefficients of competitors accordingly.

IV. Fault Section Estimation Module

Alarm processing is a stressful and time-consuming for the operators to handle. The accuracy is reduced when multiple faults, failures of protection devices, and false data are involved. An implicit disadvantage of the traditional knowledge-based systems is that they may be incapable of handling complex scenarios that are not encountered during knowledge acquisition, implementation, or validation. They may also suffer from the slowness in analysis due to involved knowledge representation and inference mechanism. Solutions based on discrete event view of Petri-nets also have several limitations. For instance, the number of initial inputs is limited and it is difficult to model inexactness and uncertainties. This paper proposes an advanced Fuzzy Reasoning Petri-nets (FRPN) diagnosis model after the structure adopted in [12]. Fuzzy Reasoning Petri-nets (FRPN) technique gains the advantages of Expert System and Fuzzy Logic, as well as parallel information processing.

A. FRPN Definition

Paper [15] has defined Fuzzy Reasoning Petri-nets (FRPN) as an 8-tuple:

$$(P, R, I, O, H, \theta, \gamma, C)$$

where:

1) $P = \{p_1, p_2, \ldots, p_n\}$ is a finite set of places or called propositions.
2) $R = \{r_1, r_2, \ldots, r_m\}$ is a finite set of transitions or called rules.
3) $I : P \times R \rightarrow \{0, 1\}$ is an $n \times m$ input matrix defining the directed arcs from propositions to rules. $I(p_i, r_j) = 1$, if there is a directed arc from p_i to r_j, and $I(p_i, r_j) = 0$, if there is no directed arcs from p_i to r_j, for $i = 1, 2, \ldots n$, and $j = 1, 2, \ldots, m$.
4) $O : P \times R \rightarrow \{0, 1\}$ is an $n \times m$ output matrix defining the directed arcs from rules to propositions.
5) $H : P \times R \rightarrow \{0, 1\}$ is an $n \times m$ matrix defining the complementary arcs from propositions to rules. $H(p_i, r_j) = 1$, if there is a complementary arc from p_i to r_j, and $H(p_i, r_j) = 0$, if there is no directed arcs from p_i to r_j, for $i = 1, 2, \ldots n$, and $j = 1, 2, \ldots, m$.
6) θ is a true degree vector. $\theta = (\theta_1, \theta_2, \ldots \theta_n)^T$, where $\theta \in [0, 1]$ means the truth degree of p_i, $i = 1, 2, \ldots n$. The initial truth degree vector is denoted by θ^0.
7) $\gamma : P \rightarrow \{0, 1\}$ is a marking vector. $\gamma = (\gamma_1, \gamma_2, \ldots \gamma_n)^T$. $\gamma_i = 1$, if there is a token in p_i, and $\gamma_i = 0$, if p_i is not marked. An initial marking is denoted by γ^0.
8) $C = \mathrm{diag}\{c_1, c_2, \ldots c_m\}$. c_i is the confidence of r_i, $j = 1, 2, \ldots, m$.

The 5-tuple (P, R, I, O, H) is the basic FRPN structure that defines a directed graph. The updates of the truth degree vector θ through execution of a set of rules describe the dynamic reasoning process of the modeled system. If the truth degree of a proposition is known at a certain reasoning step, a token is assigned to the corresponding proposition, which is associated with the value between 0 and 1. The token is represented by a dot. When a proposition p_i has no token, which means that the truth degree is unknown at that step, $\theta_i = 0$.

In order to describe the execution rules of a FRPN, the following operators are used:

1) $\oplus$: $\mathrm{A} \oplus \mathrm{B} = \mathrm{D}$, where A, B, and D are all $m \times n$-dimensional matrices, such that $d_{ij} = \max\{a_{ij}, b_{ij}\}$.
2) $\otimes$: $\mathrm{A} \otimes \mathrm{B} = \mathrm{D}$, where A, B, and D are all $(m \times p)$, $(p \times n)$, $(m \times n)$-dimensional matrices, such that $d_{ij} = \max_{1 \leq k \leq p}\{a_{ij} \cdot b_{ij}\}$.

The execution rules include enabling and firing rules.

1) A rule $r_j \in R$ is enabled if and only if p_i is marked, or $\gamma_i = 1$, $\forall p_i \in \{\text{input propositions of } r_j\}$.
2) Enabled at marking γ, r_j firing results in a new γ'.

$$\gamma'(p) = \gamma(p) \oplus O(p, r_j), \quad \forall p \in P$$

The truth degree vector changes from θ to θ'

$$\theta'(p) = \theta(p) \oplus c_j \cdot \rho_j \cdot O(p, r_j), \quad \forall p_i \in P$$

where:

$$\rho_j = \min_{p_i \in \dot{r_i}}\{x_i \mid x_i = \theta_i, \text{ if } I(p_i, r_j) = 1; \\ x_i = 1 - \theta_i \text{ if } H(p_i, r_j) = 1\}$$

and

$$\dot{r_i} = \{p_i \mid I(p_i, r_j) = 1 \text{ or } H(p_i, r_j) = 1,\ p_i \in P\}$$

3) All the enabled rules can fire at the same time. A firing vector μ is introduced such that $\mu_j = 1$, if r_j fires. After firing a set of rules, the marking and truth degree vectors of the FRPN become

$$\gamma' = \gamma \oplus [O \otimes \mu] \tag{1}$$
$$\theta' = \theta \oplus [(O \cdot C) \otimes \rho] \tag{2}$$

where $\rho = (\rho_1, \rho_2, \ldots \rho_m)^T$, which is called control vector. $\mu : T \rightarrow \{0, 1\}$ is the firing vector.

B. FRPN Model Implementation

We use a real event case that happened in Texas to implement our model. The protection system configuration for this case is shown in Fig. 4.

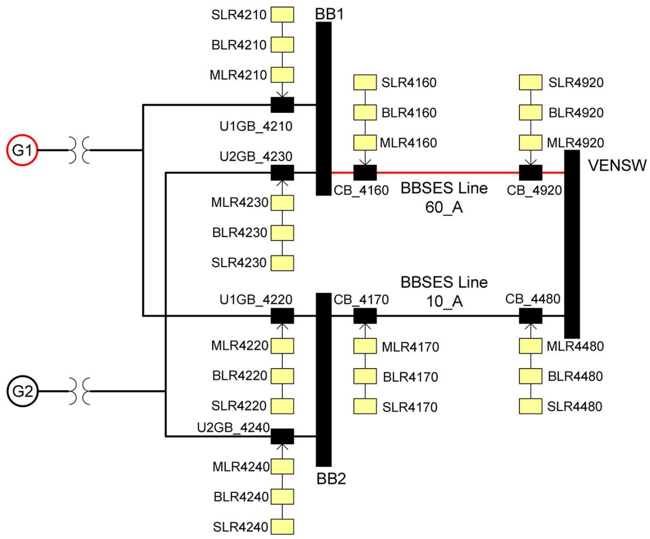


Fig. 4. Protection system configuration diagram.

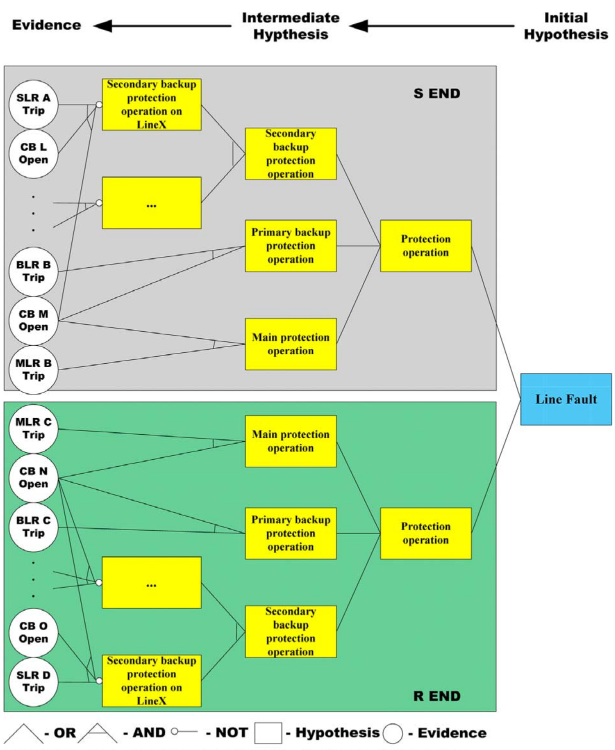


Fig. 5. Backward reasoning concept for structuring transmission line diagnosis models.

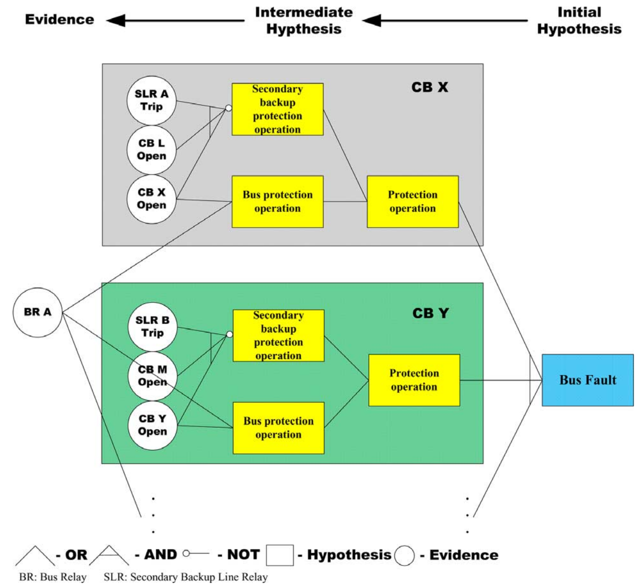


Fig. 6. Backward reasoning concept for structuring bus diagnosis models.

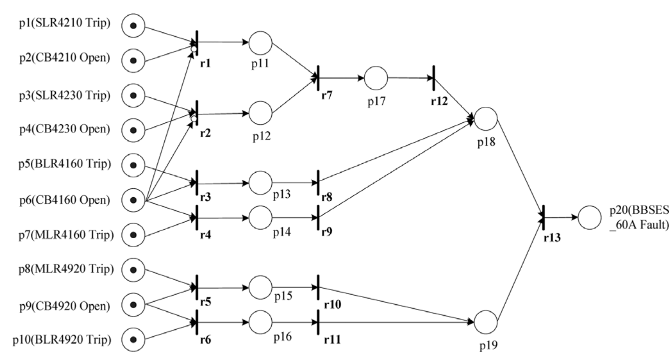


Fig. 7. A FRPN model for BBSES_60A fault.

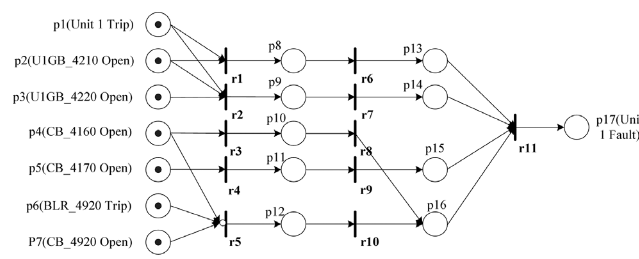


Fig. 8. A FRPN model for Unit 1 fault.

The system consists of 9 sections, including 3 buses, 2 generators, and 4 transmission lines.

When one or more faults occur on certain sections of the power system, protection devices will reach certain status accordingly. The observed circuit breaker status signals obtained from RTUs of SCADA systems are used as inputs for estimation of the faulted sections. The logic reasoning method uses the relay status obtained from the online-database to validate each candidate fault section. The strategy is to build one FRPN diagnosis model for each section of the power system. Each model establishes reasoning starting from a set of SCADA data to the conclusion of fault occurrence on its associated section with certain truth degree value.

We use backward reasoning concept to structure the FRPN diagnosis models and generalize the design for transmission lines and buses. Figs. 5 and 6 illustrate backward reasoning concept for structuring transmission line and bus models respectively. The "AND-OR" structure concisely represents all the possible combinations of main, primary backup, and secondary backup protection operations for inferring a fault.

Based on this proposed structure, all the FRPN diagnosis models can be developed. As an example, Figs. 7 and 8 show the FRPN models for the transmission and Unit 1 line BBSES_60A respectively.

The IEAP gives each proposition a "truth degree value" to illustrate the strength of confirmation as shown in Fig. 9. We use a "weighted average" operation when calculating the truth degree value to indicate the relative significance of antecedent

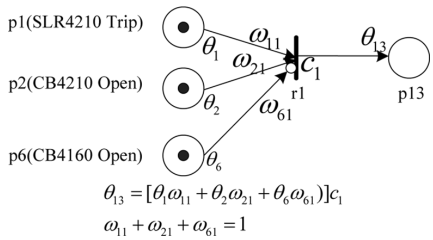


Fig. 9. A FRPN model for BBSES_60A fault.

propositions in implicating the consequent proposition. This is particularly meaningful when the cause-effect relation among antecedent propositions is considered. In our assumption, circuit breaker opening is the effect of relay trip. The "circuit breaker opens" proposition is generally given larger weight than that of the "relay trips" proposition because circuit breaker opening indicates the completion of a protection operation more directly. For example, regarding the rule r1 in Fig. 9, the proposition p5"SLR4160 Trip" will be given a weight 0.2, the proposition p2 "CB4210 Open" will be given a weight 0.4, and the proposition p6 "CB4160 Open" will be given a weight 0.4.

The benefit of the weight parameters lies in that the false data problem can be effectively handled by averaging the truth degree values of antecedent propositions. For example, when the relay BLR_4920 trips and the circuit breaker CB_4920 opens as a consequence of a fault on the bus Unit_1, and "BLR4920 Trip" is not observed. p12, which stands for "Primary backup protection operation," will still get a moderate truth degree value instead of 0 as shown in Fig. 12, hence a moderate truth degree value for the final conclusion. It is apparent that the larger the number of input data, the impact of false data is more effectively countered.

C. Execution Rules and Algorithm

Equations (1) and (2) in Section IV-A show that as long as μ and ρ are known, the next step marking and truth degree vectors can be derived from the current values. To obtain μ and ρ, an "neg" operator is used as follows:

$$\text{neg\_}\gamma^k = 1_m - \gamma^k = \overline{\gamma^k}$$
$$\text{neg\_}\theta^k = 1_m - \theta^k = \overline{\theta^k}$$

where $1_m = (1,1,\ldots 1)^T$.

μ^k is calculated as follows:

$$\mu^k = \overline{(I+H)^T \otimes \overline{\gamma^k}} \tag{3}$$

where γ^k is the marking vector.

ρ^k is calculated as follows:

$$\rho^k = ((I^T.*W^T)\cdot\theta^k + (H^T.*W^T)\cdot\overline{\theta^k}).*\mu^k \tag{4}$$

where W is the weight matrix. The ".$*$" operator can be defined as follows:

$.*$: $\mathbf{A}.*\mathbf{B}=\mathbf{D}$, where $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{D}$ are all $m\times n$-dimensional matrices, such that $d_{ij}=a_{ij}\cdot b_{ij}$.

From (1) and (3), we obtain:

$$\gamma^{k+1} = \gamma^k \oplus (O \otimes \overline{(I+H)^T \otimes \overline{\gamma^k}}) \tag{5}$$

From (2), (3), and (4), we obtain:

$$\theta^{k+1} = \theta^k \oplus ((O\cdot C)\otimes(((I^T.*W^T)\cdot\theta^k + (H^T.*W^T)\cdot\overline{\theta^k}).*\mu^k)) \tag{6}$$

To summarize, the matrix execution algorithm can be described as:

1) Read initial inputs I, O, H, C, γ^0, and θ^0.
2) Let $k=0$.
3) Compute γ^{k+1} from γ^k according to (5); Compute θ^{k+1} from θ^k according to (6).
4) If $\theta^{k+1}\neq\theta^k$ or $\gamma^{k+1}\neq\gamma^k$, let $k=k+1$, and return to step 3);
5) Otherwise the reasoning is over.

We take the FRPN diagnosis model for transmission line BBSES_60A as an example for the reasoning process. When a fault occurred on line BBSES_60A, its associated protection system operated to respond to the fault. The following signals are observed in SCADA data: SLR4210 Trip, CB4210 Open, SLR4230 Trip, CB4230 Open, BLR4160 Trip, CB4160 Open, MLR4160 Trip, MLR4920 Trip, CB4920 Open, and BLR4920 Trip. Therefore, the initial γ^0 and θ^0 are given as:

$$\gamma^0 = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]^T$$
$$\theta^0 = [0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]^T$$

The first reasoning step will result in:

$$\gamma^1 = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0]^T$$
$$\theta^1 = [0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.5610\ 0.5610\ 0.8110\ 0.8550\ 0.8550\ 0.8110\ 0\ 0\ 0\ 0]^T$$

The second reasoning step will result in:

$$\gamma^2 = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 0]^T$$
$$\theta^2 = [0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.5610\ 0.5610\ 0.8110\ 0.8550\ 0.8550\ 0.81100.5610\ 0.8550\ 0.8550\ 0]^T$$

The third reasoning step will result in:

$$\gamma^3 = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1]^T$$
$$\theta^3 = [0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0.5610\ 0.5610\ 0.8110\ 0.8550\ 0.8550\ 0.81100.5610\ 0.8550\ 0.8550\ 0.8550]^T$$

Thus the conclusion will be that a fault occurred on the transmission line BBSES_60A with a truth degree value 0.8550.

Another example would be bus Unit_A fault, BLR4920 Trip is missing in the SCADA data due to the transmission error or failure to operate. The conclusion will be that a fault occurred on the bus Unit_A with a truth degree value 0.8550.

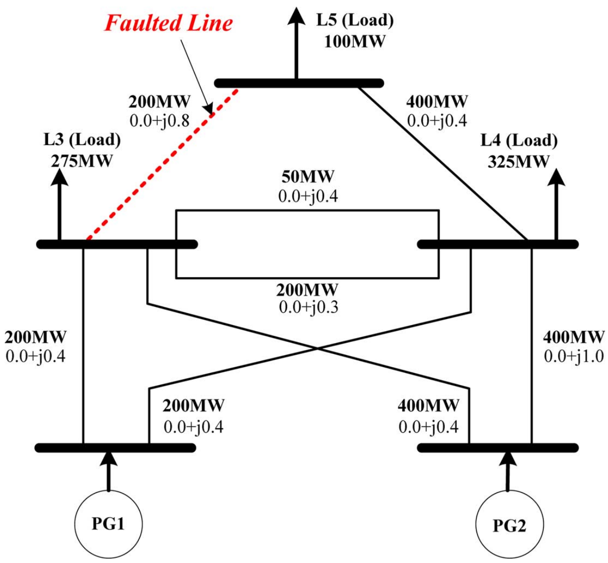


Fig. 10. A FRPN model for Unit 1 fault.

V. Economic Alarm Processor Module

Once the fault section estimation module detects a fault in certain region, the economic alarm processor firstly checks if there is any thermal violations and calculates the changes in the LMPs, total generation cost and congestion revenue etc. Then it gives some suggested re-dispatch actions to optimize the whole system. The objective of the module is to minimize the total generation cost. Since the market transactions have already been scheduled prior to the fault event, we may consider the demand is perfectly inelastic, thus minimizing the total cost is the same as maximizing the total social welfare. Therefore, the problem can be written as:

$$\begin{aligned}
&\min_{P_{Gi}} && \sum_{i=1}^{N_G} C_i(P_{Gi}) \\
&\text{s.t.} && \sum_{i=1}^{N_G} P_{Gi} = \sum_{i=1}^{N_L} P_{Li}\ (\text{Demandnd} = \text{Supply}) \\
&\text{and} && P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \text{ for } i = 1, \ldots, N_G \\
&\text{and} && P_{Lj}^{\min} \le P_{Lj} \le P_{Lj}^{\max} \text{ for } j = 1, \ldots, N_L \\
&\text{and} && |F_{ij}| \le F_{ij}^{\max} \text{ if } z_{ij} = 1, |F_{ij}| = 0 \text{ if } z_{ij} = 0
\end{aligned}$$

P_{Gi} is the generation from generator i, and N_G is the total number of generators. P_{Lj} is the demand for each load j, and N_L is the total number of loads. C_i is the generation cost for generator i, and F_{ij} denotes the power flow from bus i to bus j. $z_{ij} = 1$ when line ij is operating normally, $z_{ij} = 0$ when a fault is detected on line ij. To simply demonstrate the concept, we assume the following parameters for the same system as in Fig. 10 and Table I:

The economic alarm processor module then sends signal changes including the LMPs, congestions, shadow prices etc. to the system operator and market participants, which allows them to utilize information on a variety of levels:

- To access the short term transmission needs in the system.
- To allow for operators to re-dispatch generators based on scheduled transactions and real time market needs.

TABLE I
Test Case Data

	Reactance x (p.u.)	Capacity (MW)
Line 1-3	0.4	200
Line 1-4	0.4	200
Line 2-3	0.4	400
Line 2-4	1.0	400
Line 3-4-1	0.4	50
Line 3-4-2	0.3	200
Line 3-5	0.8	400
Line 4-5	0.4	400
0< P_{G1}<1000 MW, C_1 = 20 P_1\$/hour,0< P_{G2}<1000 MW,C_2 = 15 P_2\$/hour		
L_3 =275MW	L_4 =325MW	L_5 =100MW

- To assist in making transmission operating decisions optimal for economic efficiency as well as for system reliability.
- To allow market participants to identify trends in LMP, line loading and demand levels in order to find/make transactions in the near future in anticipation of these trends.

The IEAP could be implemented in the control center by ISO directly or by a third party, who would receive system state and market data from the ISO. Those data may also be available for sale through private companies such as GenScape [16]. However, it is still a question to what extent system's data should be open to the public. The system state data would be valuable to market participants, but the distribution of this data may raises cyber security issues [5].

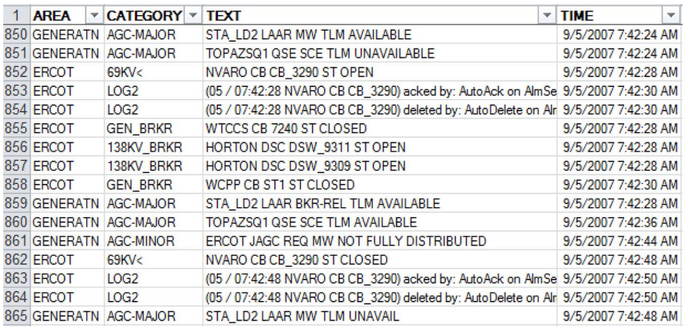
The IEAP would give the operator an alarm that the line 3-5 is faulted, and the operator has to run the optimal power flow again without the faulted line. The traditional way to run optimal power flow will take all the currently-feasible transmission lines into consideration. However, it is interested to note that [10] raised an idea of "Optimal Transmission Switching." Assumed that taking a "healthy" transmission line out of service will not result in degrading current system reliability, the potential economic savings can be achieved. In the case study presented next, we will also verify this idea by taking the redundant element out to optimize the whole system benefit.

VI. Case Study

A. Background

On September 5, 2007, a tornado in the area resulted in the tripping of two 345 kV lines and two generators connected to the same substation. Case data taken from the Supervisory Control and Data Acquisition (SCADA) database of the EMS monitoring the area are used. The first data scan was captured at approximately 07:49 A.M., before the event occurred, and the second was captured at approximately 07:54 A.M., just after the event occurred.

There were 2125 alarm messages that appeared within only 45 minutes, some a screen shot illustrated in Fig. 11. Obviously processing such large number of alarms is beyond the capacity of any operator to handle. Thus, operators may not be able to respond to the unfolding events in time, and even worse, the interpretation by the operators may either be wrong or in conclusive. ERCOT operators also indicated in interviews that the list containing large number of alarms provides little help for them.



1	AREA	CATEGORY	TEXT	TIME
850	GENERATN	AGC-MAJOR	STA_LD2 LAAR MW TLM AVAILABLE	9/5/2007 7:42:24 AM
851	GENERATN	AGC-MAJOR	TOPAZSQ1 QSE SCE TLM UNAVAILABLE	9/5/2007 7:42:24 AM
852	ERCOT	69KV<	NVARO CB CB_3290 ST OPEN	9/5/2007 7:42:28 AM
853	ERCOT	LOG2	(05 / 07:42:28 NVARO CB CB_3290) acked by: AutoAck on AlmSe	9/5/2007 7:42:30 AM
854	ERCOT	LOG2	(05 / 07:42:28 NVARO CB CB_3290) deleted by: AutoDelete on Alr	9/5/2007 7:42:30 AM
855	ERCOT	GEN_BRKR	WTCCS CB 7240 ST CLOSED	9/5/2007 7:42:28 AM
856	ERCOT	138KV_BRKR	HORTON DSC DSW_9311 ST OPEN	9/5/2007 7:42:28 AM
857	ERCOT	138KV_BRKR	HORTON DSC DSW_9309 ST OPEN	9/5/2007 7:42:28 AM
858	ERCOT	GEN_BRKR	WCPP CB ST1 ST CLOSED	9/5/2007 7:42:30 AM
859	GENERATN	AGC-MAJOR	STA_LD2 LAAR BKR-REL TLM AVAILABLE	9/5/2007 7:42:28 AM
860	GENERATN	AGC-MAJOR	TOPAZSQ1 QSE SCE TLM AVAILABLE	9/5/2007 7:42:36 AM
861	GENERATN	AGC-MINOR	ERCOT JAGC REQ MW NOT FULLY DISTRIBUTED	9/5/2007 7:42:44 AM
862	ERCOT	69KV<	NVARO CB CB_3290 ST CLOSED	9/5/2007 7:42:48 AM
863	ERCOT	LOG2	(05 / 07:42:48 NVARO CB CB_3290) acked by: AutoAck on AlmSe	9/5/2007 7:42:50 AM
864	ERCOT	LOG2	(05 / 07:42:48 NVARO CB CB_3290) deleted by: AutoDelete on Alr	9/5/2007 7:42:50 AM
865	GENERATN	AGC-MAJOR	STA_LD2 LAAR MW TLM UNAVAIL	9/5/2007 7:42:48 AM

Fig. 11. Screen shot of alarm messages during fault in Control Center.

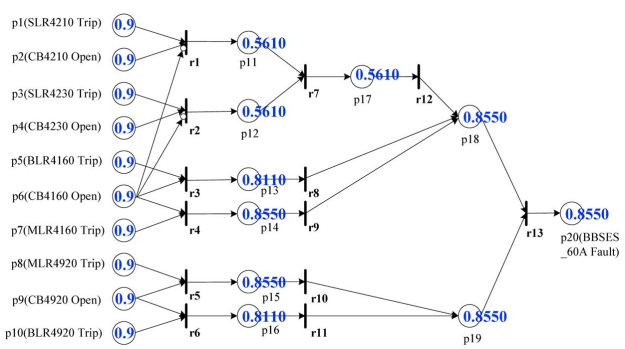


Fig. 12. FRPN model analysis procedure for Line BBSES_60A.

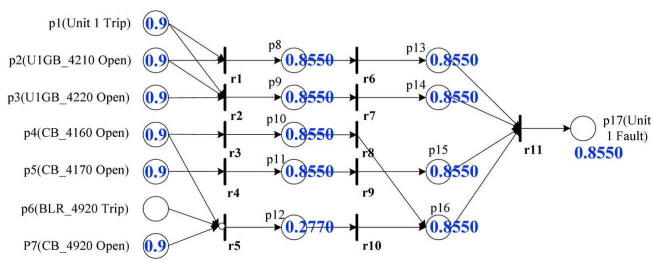


Fig. 13. FRPN model analysis procedure for Unit 1.

They normally just make phone calls to look up for the faulted section, which may take 15–20 minutes and even longer.

B. Simulation Results

Case 1: This case assumes the circuit breaker is tripped by the associated relays, thus allowing the relay status to be obtained to validate the fault. The operation of circuit breakers CB4210, CB4220, CB4160, CB4920 is detected, see in Fig. 12.

Diagnosis Result: Line BBSES_60A is faulted, and its truth value is 0.8550.

When the signal designating that BBSES_60A (which is line 3-5) is out of operation is sent to the economic alarm processor module, the current situation is quickly analyzed, and a summary report is shown in Table II.

In this example, the loss of line 3-5 causes the line 3-4-1 to exceed its thermal capacity. To relieve it from violating the limit, the module gives two suggested actions. The first one is to adjust the generation which results in an increase in the total generation cost. The second option is to take the line 3-4-1 out assuming no other reliability or security standards are violated, and the system total generation cost will remain the same.

TABLE II
ECONOMIC ALARM PROCESSOR SUMMARY REPORT

Before the fault:	
Fault detected?	No
Any thermal violations?	No
Generation 1	300 MW
Generation 2	400 MW
Total Generation Cost	12000 $/hour
After the fault: (if no action is taken)	
Fault detected?	Line 3-5 is out
Any thermal violations?	Line 3-4-1 exceeds the limit by 2MW
Generation 1	300 MW
Generation 2	400 MW
Total Generation Cost	12000 $/hour
Suggested Actions:	
Option 1	Increase P_{G1} and decrease P_{G2}
Fault detected?	Line 3-5 is out
Any thermal violations?	No
Generation 1	330 MW
Generation 2	370 MW
Total Generation Cost	12150 $/hour
Changes in Total Generation Cost	Increased by 150$/hour
Option 2	Taking Line 3-4-1 out.
Fault detected?	Line 3-5 is out
Any thermal violations?	No
Generation 1	300 MW
Generation 2	400 MW
Total Generation Cost	12000 $/hour
Changes in Total Generation Cost	No

TABLE III
ECONOMIC ALARM PROCESSOR SUMMARY REPORT

Before the fault:	
Fault detected?	No
Any thermal violations?	No
Generation 1	300 MW
Generation 2	400 MW
Total Generation Cost	12000 $/hour
After the fault: (if no action is taken)	
Fault detected?	Unit 1 is out
Any thermal violations?	System is unbalanced
Generation 1	0 MW
Generation 2	400 MW
Total Generation Cost	
Suggested Actions:	
Option 1	Increase P_{G2} by 300MW
Fault detected?	Unit 1 is out
Any thermal violations?	Line 2-3 exceeds the limit by 84MW Line 3-4-1 exceeds the limit by 5.5MW
Generation 1	0 MW
Generation 2	700 MW
Total Generation Cost	10500 $/hour
Changes in Total Generation Cost	Decreased by 1500 $/hour
Option 2	Find alternative generations from reserve services or real-time market
Option 3	Cut the load

Case 2: This case assumes that no protective relay signals are available. Unit 1 tripped, and operation of circuit breakers CB4210, CB4220, CB4160, CB4170, and CB4920 is detected.

Diagnosis Result: Unit 1 is faulted, and its truth value is 0.8550.

When the signal designating that Unit 1 is lost is sent to the economic alarm processor module, the IEAP will analyze the system state and market data and give a summary report shown in Table III.

When PG1 is lost, the system is unbalanced and on the edge of collapse. The system operator has to find a solution to restore the system immediately. The easiest and most intuitive way would

TABLE IV
IMPACTS OF UNAWARE SYSTEM TOPOLOGY CHANGES

	Real price when retrieve the IEAP report on time	Fail to retrieve the latest fault event information	Differences
LMP 3	8 \$/MWh	15 \$/MWh	7 \$/MWh
LMP 4	28 \$/MWh	15 \$/MWh	13 \$/MWh
LMP 5	28 \$/MWh	15 \$/MWh	13 \$/MWh
Gen 1	Output = 330 MW Revenue = 6600 \$/hr	Output = 300 MW Revenue = 6000 \$/hr	Revenue loses 600 \$/hr
Gen 2	Output = 370 MW Revenue = 5550 \$/hr	Output = 400 MW Revenue = 6000 \$/hr	Revenue gains 450 \$/hr
Load 1	Pays 2200 \$/hr	Pays 4125 \$/hr	Cost goes up 1925 \$/hr
Load 2	Pays 10500 \$/hr	Pays 5625 \$/hr	Cost goes down 4875 \$/hr
Load 3	Pays 2800 \$/hr	Pays 1500 \$/hr	Cost goes down 1300 \$/hr

be increase PG2 by 300 MW. However, two lines would exceed the thermal limits even though the total generation cost decreased. Thus, the operator has to find alternative generation from reserve services or real-time market, which will certainly have a great impact on the market participants' bidding strategies. The last solution would be to cut the load in node 3, 4, or 5, but the system operator has to compensate the customers a lot.

C. Impacts on Market Participants

Participants are very sensitive to every single event happened in the electricity market. The LMPs are calculated every five minutes in ERCOT's real time market. Market operators from ERCOT admitted that it is possible that EMS (Energy Management System) fails to deliver the latest fault event and topology change information to MMS (Market Management System). Price errors caused from those inaccurate system inputs could be tremendous. And the impacts will arise in varies aspects.

The first impact will be on the "traditional" MPs, such as generation entities and load entities. Take case 1 as an example, since there is congestion after the fault happens. Failure to aware the topology change will result in a LMP differences, which lead to huge economic profits/losses, as shown in Table IV.

From the tables above, Generation 1 will lose 600 \$/hr, and customers in Load 1 have to suffer a cost increase. On the other hand, Generation 2 and customers in Load 2 and 3 will enjoy an unexpected profit due to the unawareness of the system topology changes.

The second impact is related to the Congestion Revenue Rights (CRR), which will involve many big hedge fund and investment bank participants.

CRR is a purely financial instrument and does not represent a right to receive, or obligation to deliver physical energy [1]. ERCOT allocates a portion of the available CRRs to Non Opt In Entities (NOIEs) as a pre-assigned CRR (PCRR) and auctions the remaining capacity monthly and annually. Most CRRs are tradable in the CRR auction, in the day-ahead market, or bilaterally. A typical type of CRRs would be Point-to-Point (PTP) CRR which is between a designated point of injection (source) and point of withdrawal (sink). PTP CRRs might be purchased in the form of PTP option or PTP obligation. The charge and payment are based on the difference in LMPs between source and sink, i.e., the holder of an M megawatt CRR from a to b at time t receives:

$$\text{CRR revenue} = M * [\text{LMP}(a)\text{–LMP}(b)]$$

Back to case 1, for instance, if a MP holds 100 MW PTP obligation from node 4 to node 3 at the time when fault happens, he would have gained $(28 - 13) * 100 = 1500$ \$/hr profit. However, due to the lack of the timely system information, he receives nothing and loses the obligation payment.

In real market world, the numbers are in millions. Market operators claims that they may correct the price errors after they found the false input data. However, it will take a tedious process and may raise a lot of other problems related to the contracts and protocols.

D. Discussion

One or more faults occurring in the system could trigger numerous alarms, and those alarms will put the system/market operation into alert state. Those alarms will be only sent to the system operator to verify the fault and take appropriate actions to restore the system. The processed information could be distributed to all the market participants for their future strategies in the market.

From the simulation test, we may draw the conclusion that our proposed Intelligent Economic Alarm Processor model works properly for the practical cases, and have the following characteristics compared with those traditional solutions:

- Take electrical grid alarms and power market schedules and trends, such as LMPs and prices, as our inputs.
- Have the system operational alarms, fault severity indications and solutions, as well as the impact on the electricity market as our outputs.
- Benefit for both system and market operators, and all other market participants.
- Greatly reduce the processing time while increase the accuracy.
- Avoid price errors that will result in unexpected costs and unearned profits.

VII. CONTINGENCY-BASED STRATEGIC BIDDING MODEL CONCEPT

The MPs' objectives are to maximize their own benefits while these may have a negative effect on maximizing the total social welfare.

Based on the current bidding strategies and models [17], [18], we could assume that each market participants bids a linear supply/demand function. They will chooses the coefficients in the linear function to maximize their own benefits, subject to expectations about how competitors will bid. However, those bidding models usually don't consider the real-time unexpected contingencies or uncertainties, such as generator outages, line outages or demand fluctuations.

Note that the IEAP could be used to send "announcement" by ISO to alert MPs that a "market restorative" action is about to be initiated and the LMPs may be increasing or decreasing. This would give MPs time to plan their response in advance of the price change and make a "guess" of their competitor's response to that. They could quickly adjust the system parameters and rival participants coefficients in their model and make a profit out of that. In paper [16], the bidding strategy problem was modeled as a stochastic optimization problem and solved using Genetic Algorithm. Numerical examples have shown that under unsymmetrical situations that MPs who have imperfect market information will suffer great profit reduction.

VIII. Conclusion

From the review of the relationship between the grid and market operation, it may be concluded that new approach to integrate grid control and market operations taking into account both good engineering practices and appropriate economic incentives needs to be implemented. Our IEAP model takes the best aspects of the use of existing artificial intelligent techniques to interpret alarms and extends it for electricity market use. In summary, our IEAP provides the following advantages:

- The fault alarm analysis and economic summary report can be generated automatically and immediately after the fault occurs with an explanation of the cause-effect relationship associated with the fault and recommendations to optimize the grid's total benefit.
- The FRPN models can be built in advance based on electricity grid and protection system configurations and stored in files. That way the FRPN models can be easily modified according to the changes of input data as well as electricity grid and protection system configuration.
- The predicated limitations of available transmission capacity (ATC) that is problematic can be identified when caused by a fault and power transfer needs as a consequence of such events can be anticipated.
- While the system operation data may not be available to all the MPs due to cyber security reasons, a quick and accurate analysis IEAP report will benefit both system and market operators, and all other market participants, to avoid unnecessary price errors that will cause big profits/losses.

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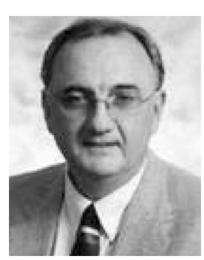

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