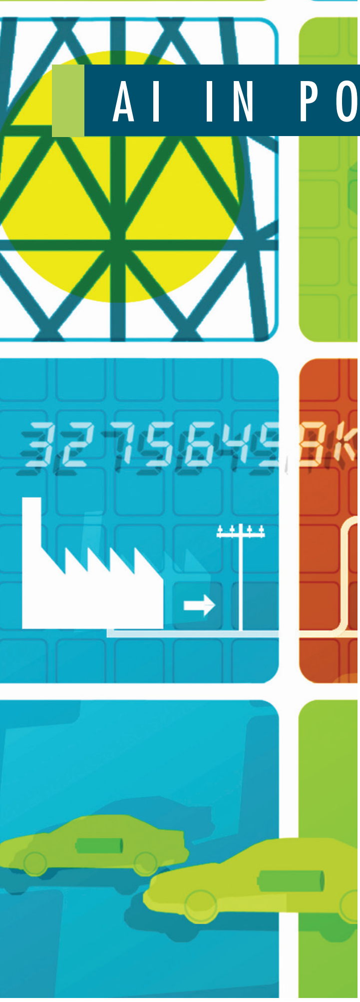

Grid Monitoring and Market Risk Management

Yufan Guan and Mladen Kezunovic, *Texas A&M University*

The Intelligent Economic Alarm Processor analyzes thousands of alarm messages to provide recommendations that optimize the total economic impact under fault scenarios in electricity markets.

The advent of electricity market deregulation has placed great emphasis on information availability and analysis and the subsequent decision making to optimize system operation in a competitive environment. This creates a need for better ways to correlate market activity with the physical grid-operating states in real time and share such information among market participants. Command and control choices might result in different financial consequences for market participants and severely impact their profits. The effects are both short term, as in day-ahead and real-time markets for energy, reserves, and congestion relief, and long term, as in investments in transmission and generation capacity. Because of this, new solutions are necessary to integrate grid control and market operations while accounting for both good engineering practices and appropriate economic incentives.

Past studies have illustrated the relationship between physical grid operations and market activities from various aspects. For example, one described the interface and persistent gap between market and grid operations in restructured electricity markets along with lessons learned through the restructuring experience in the US and abroad.[1] Another discussed how to measure and manage the market risks in operations in both operational and financial ways.[2] Researchers have proposed models to demonstrate the financial effects of power purchase based on the probability of contingency occurrence and consequences. The *economic alarm* concept was first raised to augment conventional electrical alarms and notify operators and market participants of changes in operating and economic conditions in an electric power system.[3] The initial study ranked alarms based on the economic severity and a set of predetermined events that would give suppliers the ability to exercise market power in response to an alarm.

Alarm processing is an important part of electricity grid operations that has been a traditional feature of the power-grid energy management system (EMS) studied over the past few decades,[4] and researchers have developed several new expert system approaches.[5,6] Despite the variety of proposed solutions, however, operators still need a better way to monitor the system than what existing alarm-processing solutions offer. Because power system events affect both the power system's operation and the power market, the importance of an electric event should be expressed in terms of the economic importance, and the economic impact should be correlated with electrical alarms.[3]

1541-1672/11/$26.00 © 2011 IEEE
Published by the IEEE Computer Society

In this article, we extend our previous Intelligent Alarm Processor (IAP) work by incorporating economic alarms. We first give a list of the fault-occurrence possibilities based on the Supervisory Control and Data Acquisition (SCADA) and intelligent electronic device (IED) signals the system processes using a fuzzy-reasoning Petri net (FRPN) model.[7,8] Following these events, our solution calculates and analyzes changes in power flows, locational marginal pricing (LMP), and other indices. Thus, we provide a closer cause-effect relationship between the physical power world and the market and translate both physical and economic alarms into easy-to-understand, real-time information.

Grid/Market Relationship and ISO Responsibility

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 grid operations. Schedules from the forward markets are implemented in the real-time dispatch, and the system operator responsible for balancing and regulation selects and dispatches resources made available through the markets to provide ancillary services.

When some operating parameters, such as voltage and current, exceed acceptable limits, the system shifts spontaneously (see the dotted lines in Figure 1) to an emergency state. The result is usually an automatic control action (see the solid lines in Figure 1), such as the tripping of a relay, which takes the system into a more acceptable, but not fully functional, restorative state. Analogous states and transitions also apply in power markets, with some notable differences, as Table 1 shows.

The independent system operator's basic responsibilities include monitoring system security functions and redispatching 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. Figure 2 shows the ISO's reliability- and market-related functions at various sizes and timescales.[9]

Based on the assumption that the system reliability is not immediately threatened when certain fault events occur in the system, our Intelligent Economic Alarm Processor (IEAP) model gives market participants advanced notice of an imminent need to serve scheduled loads, find replacement transmission transfer capacity, or meet service needs. Market participants might often be able to find economic benefits and adjust their market strategies accordingly if they are given such advanced notice.

Grid/Market Integrated Model

The IEAP can be implemented in a control center to assist the grid operator in rapidly identifying faulted sections and market operation management. Figure 3 illustrates the application's structure and its SCADA support infrastructure.

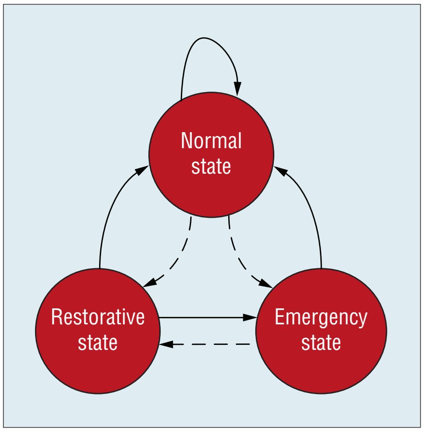

Figure 1. System operating states. The dotted lines indicate when the system shifts spontaneously, and solid lines show an automatic control action.

In such a solution, field data such as relay-trip signals and circuit-breaker status signals are acquired by the SCADA system's remote terminal units (RTUs). In the control center, the SCADA master computer puts the input data into a real-time database and updates them at each scan time.

The IEAP application includes two modules, the *fault-section estimation application* and the *economic alarm processor*. The first module uses the fuzzy-reasoning Petri net (FRPN) diagnosis model and data in the real-time database corresponding to each section in the rough candidate set. 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 will be included in the refined fault-candidate set. Such a set is presented to the grid operator for decision making.

In the second module, the processor initially analyzes the fault severity based on the information retrieved

Table 1. Market operating states.

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

*Market participants (MPs) include generator companies, transmission owners, load-serving entities, and other nonasset owners such as energy traders.

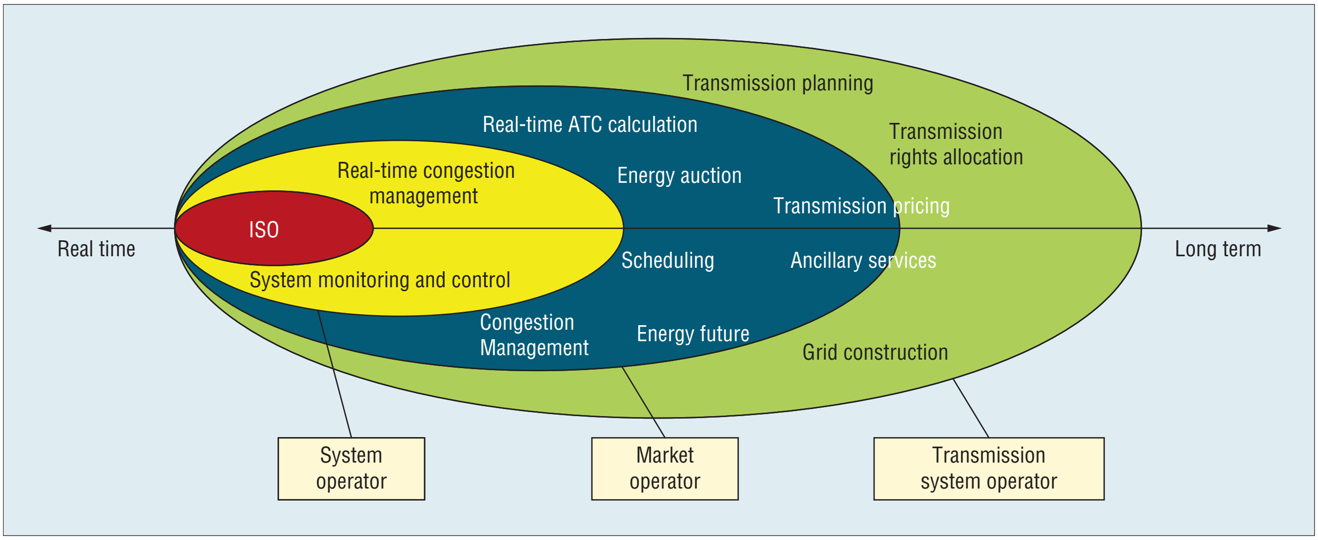

Figure 2. Independent system operator's (ISO's) basic responsibilities. We show the reliability- and market-related functions at various sizes and timescales (in a continuum from real time to long term).

from the fault-section estimation module and gives the changes in LMPs, total generation cost, congestion revenue, and so forth with electricity market schedules and trends. Then, the grid operator will carry out various suggested restorative actions to optimize the overall benefit.

Fault-Section Estimation Module

Alarm processing is a stressful, time-consuming, and accuracy-restricted effort when multiple faults, failures of protection devices, and false data are involved. Researchers have recently spent a lot of effort on filtering and suppressing alarms based on the AI techniques in practical systems.[4,10] So far, the major AI techniques used include the following:

- Expert system (ES) techniques are well suited for a diagnosis problem such as fault-section estimation because they mimic the behavior of fault-analysis experts who perform fact-rule comparisons and search consequent steps.[5,6]
- Fuzzy logic (FL) techniques offer a convenient means for modeling inexactness and uncertainties, making them a powerful solution to handle imprecise and incomplete data.
- Petri nets (PN) techniques possess the characteristics of graphical discrete-event representation and parallel information processing.

An implicit disadvantage of traditional knowledge-based systems is that they might be unable to handle complex scenarios that they did not encounter during knowledge acquisition, implementation, and validation. They might also suffer from slow analysis because of an involved knowledge representation and inference mechanism. Solutions based on a discrete event view of Petri nets also have several limitations.

Our proposed FRPN technique gains the advantages of expert systems and fuzzy logic as well as parallel information processing. Some of the disadvantages of previously mentioned individual techniques might be offset by the benefits of combining these techniques. (We illustrated the alarm diagnosis algorithm and model we used for this case in an earlier work.[7]) Figure 4 shows the protection system configuration for this case.

When one or more faults occur on certain sections of the power system, protection devices will also reach a certain status accordingly. The observed circuit-breaker status signals obtained from SCADA system RTUs are used as inputs to estimate the faulted sections. The logic-reasoning method uses the relay status obtained from the real-time 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 a certain truth degree value, as Figure 5 shows.

We use a backward-reasoning concept to structure the FRPN diagnosis models and generalize the design for transmission lines and buses (see Figure 5). 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, we can develop all the FRPN diagnosis models. As an example, Figure 6 shows the FRPN models for the transmission line BBSES_60A and an example for the weighted-average operation.

The IEAP gives each proposition a truth degree value to illustrate the strength of confirmation. We use a weighted-average operation when calculating the truth degree value of a consequent proposition from the

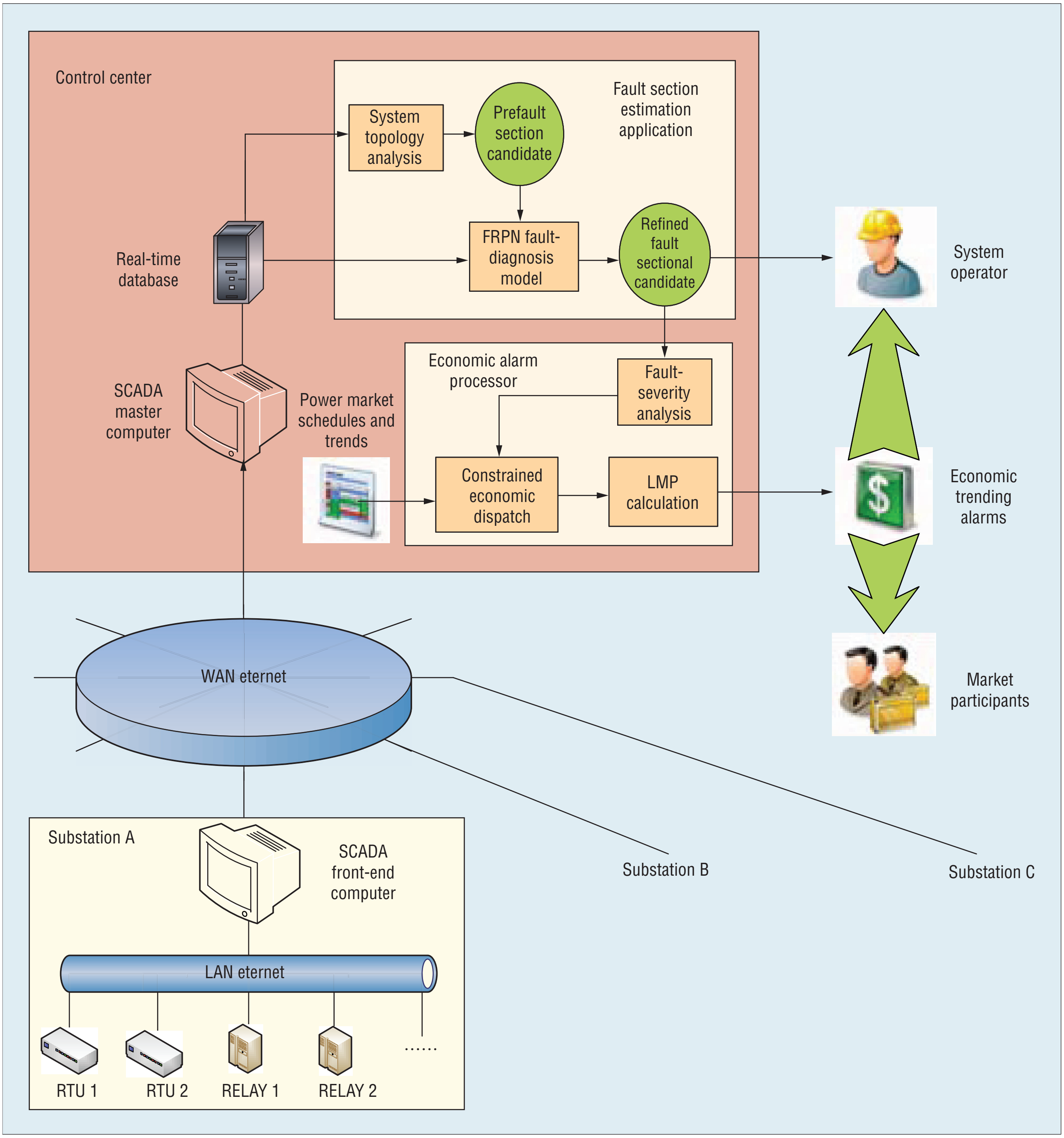

Figure 3. Intelligent Economic Alarm Processor (IEAP) structure. Support for Supervisory Control and Data Acquisition (SCADA) is also included in the infrastructure. (RTUs are remote terminal units.)

truth degree values of its antecedent propositions.

The weighted-average operation has two benefits. First, we recognize the relative significance of antecedent propositions in implicating the consequent proposition using the weights of antecedent propositions. This is particularly meaningful when considering the cause-effect relation among antecedent propositions. In our assumption, the opening of the circuit breaker is the effect of a relay trip. The "circuit breaker opens" proposition is generally given larger weight than that of the "relay trips" proposition because a circuit breaker opening indicates

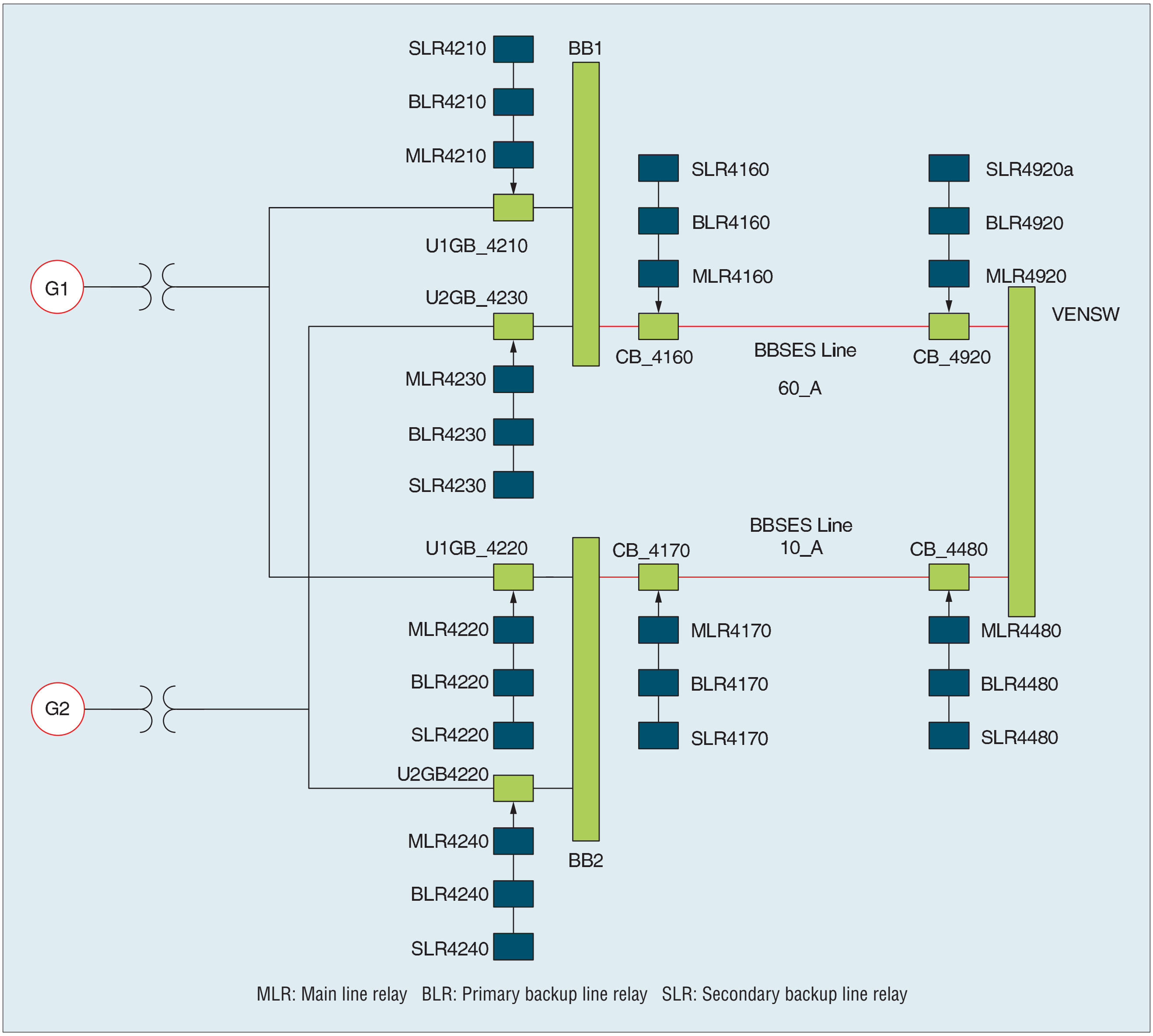

Figure 4. Protection-system configuration diagram. The protection-system configuration consists of nine sections, including three buses, two generators, and four transmission lines.

the completion of a protection operation more directly. For example, regarding the rule r3 in Figure 6, the proposition p5 "BLR4160 Trip" will be given a weight 0.4, and the proposition p6 "CB4160 Open" will be given a weight 0.6.

Second, we effectively handle the false-data problem by averaging the truth degree values of antecedent propositions. For example, when the relay MLR4160 trips and the circuit breaker CB4160 opens as a consequence of a fault on the line BBSES_60A and "MLR4160 Trip" is not observed, p15 (which stands for "main protection operates") will still get a moderate truth degree value instead of 0, which is a moderate truth degree value for the final conclusion. Thus, the larger the number of input data, the more effectively we can counter the impact of false data.

Economic Alarm Processor Module

Once the fault-section estimation module detects a fault, the economic alarm processor first checks if there are any thermal violations and calculates the changes in the LMPs, total generation cost and congestion revenue, and so on. Then, it gives a suggested redispatch action to optimize the total social welfare or some other agreed upon "equality" criteria. The module's objective is to minimize the total generation cost. Because the market transactions have already been scheduled prior to the fault event, we can consider the demand

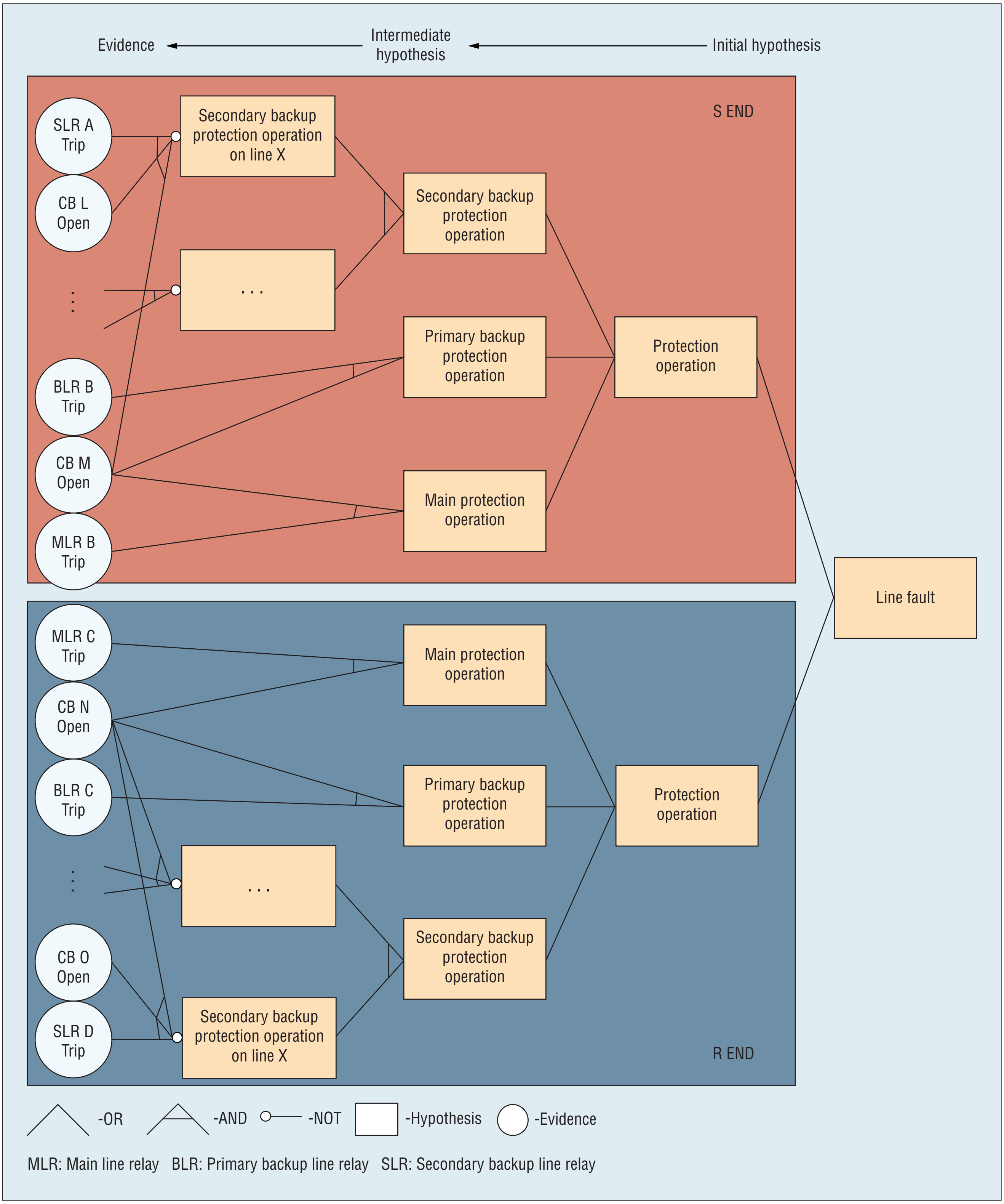

Figure 5. Backward-reasoning concept for structuring transmission line diagnosis models. Each model establishes reasoning starting from a set of SCADA data to the conclusion of fault occurrence on its associated section with a certain truth degree value.

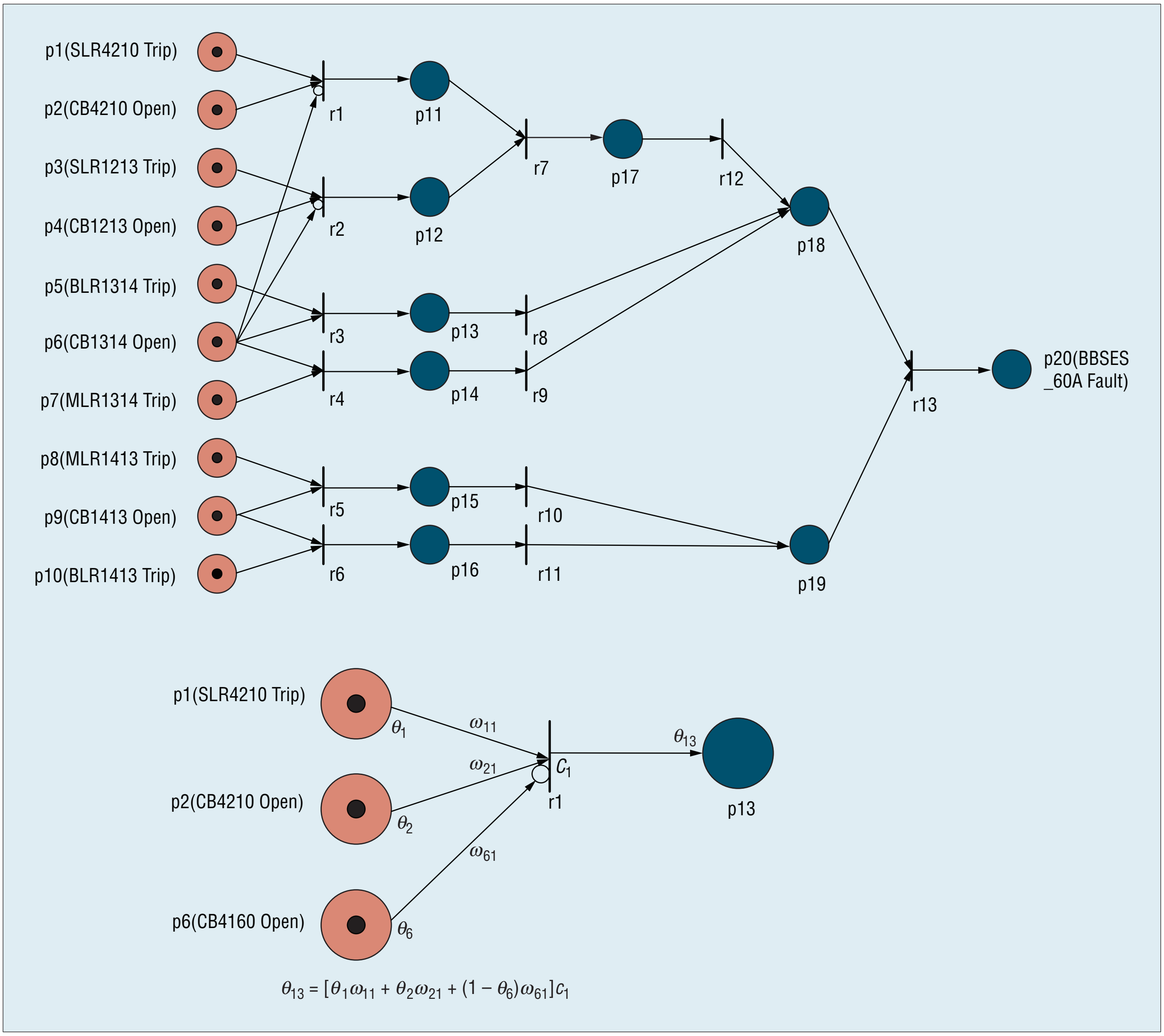

Figure 6. A fuzzy-reasoning Petri net (FRPN) model for the BBSES_60A fault. We use an example for the weighted-average operation.

inelastic, so minimizing the total cost is the same as maximizing the total social welfare or equality criteria. Therefore, we can write the problem as

$$\min_{P_{Gi}} \sum_{i=1}^{N_G} C_i(P_{Gi})$$

$$\text{subject to} \quad \sum_{i=1}^{N_G} P_{Gi} = \sum_{i=1}^{N_L} P_{Li} (\text{Demand} = \text{Supply})$$

$$\text{and} \quad P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \quad \text{for } i = 1,\ldots,N_G$$

$$\text{and} \quad P_{Lj}^{\min} \le P_{Lj} \le P_{Lj}^{\max} \quad \text{for } j = 1,\ldots,N_L$$

$$\text{and} \quad |F_{ij}| \le F_{ij}^{\max} \text{ if } z_{ij} = 1, |F_{ij}| = 0 \text{ if } z_{ij} = 0$$

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, and $z_{ij} = 0$ when a fault is detected on line ij. To simply demonstrate the concept, we assume the parameters for the system in Figure 7 and Table 2.

The economic alarm processor module will then send signals about changes including the LMPs, congestion, shadow prices, and so forth to the grid operator and market participants. This information

- gives them access to the short-term transmission needs in the grid;
- lets operators redispatch generators based on scheduled transactions and real-time market needs;
- assists operators in making transmission operating decisions optimal for economic efficiency as well as grid reliability; and

- lets market participants identify trends in LMP, line loading, and demand levels to find and make transactions in the near future in anticipation of these trends.[4]

In this case, we know in advance that the line 3-5 is faulted. The traditional response is to run optimal power flow based on the current topology. An earlier work raised the idea of *optimal transmission switching*.[11] Assuming that taking a transmission line out of service will not result in degrading current grid reliability, we can achieve potential economic savings. In the following case study, we verify this idea by taking the redundant element out to optimize the total social welfare or equality criteria.

Case Study

On 5 September 2007, a tornado in Texas tripped two 345 kV lines and two generators in one substation. We used case data taken from the SCADA database that was used by the EMS to monitor the area. The first was captured at approximately 7:49 a.m., before the event occurred, and the second was captured at approximately 7:54 a.m., just after the event occurred.

This case assumes that the circuit breaker's operation is tripped by the associated relays, thus allowing the relay status to be obtained to validate the fault. Figure 8 shows that circuit breakers CB4210, CB4220, CB4160, and CB4920 were detected. As a result, Line BBSES_60A is faulted, and its truth value is 0.8550.

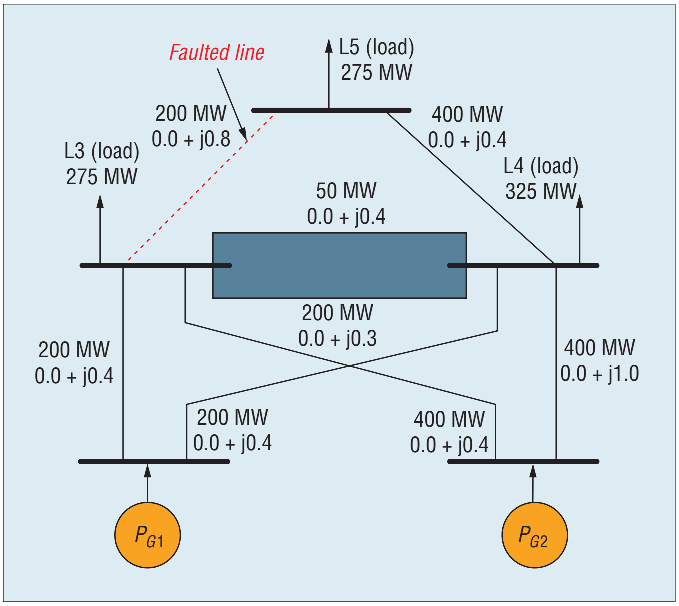

Figure 7. Five-bus test system. This one-line diagram shows the faulted system with two generations and three load nodes.

When the signal indicating 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. Table 3 shows the prepared summary report.

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 is to adjust the generation, which results in an increase in the total generation cost. The second is to take the line 3-4-1 out, assuming no other reliability or security standards are violated, and the system total generation cost remains the same.

One or more faults occurring in the grid could trigger numerous alarms, and those alarms will put the grid/market operation into alert state. Those alarms will be only sent to the grid operator to verify the fault and take appropriate actions to restore the grid. The processed information could be distributed to all the market participants for their future strategies in the market. Table 4 compares existing approaches and our solutions.

The review of the relationship between grid and market operation indicates that our approach can help to integrate grid control and market operations. Our IEAP model takes the best aspects of existing AI techniques and extends them

Table 2. Test case data.

Lines	Reactance x (per unit)*	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
$0 < P_{G1} < 1{,}000$ MW, $C_1 = 20\ P_1$ \$/hour, $0 < P_{G2} < 1{,}000$ MW, $C_2 = 15\ P_2$ \$/hour		
$L_3 = 275$ MW	$L_4 = 325$ MW	$L_5 = 100$ MW

*In a alternating-current electrical circuit (RLC series circuit), reactance is the imaginary part of impedance and is caused by the presence of inductors or capacitors in the circuit, denoted by x.

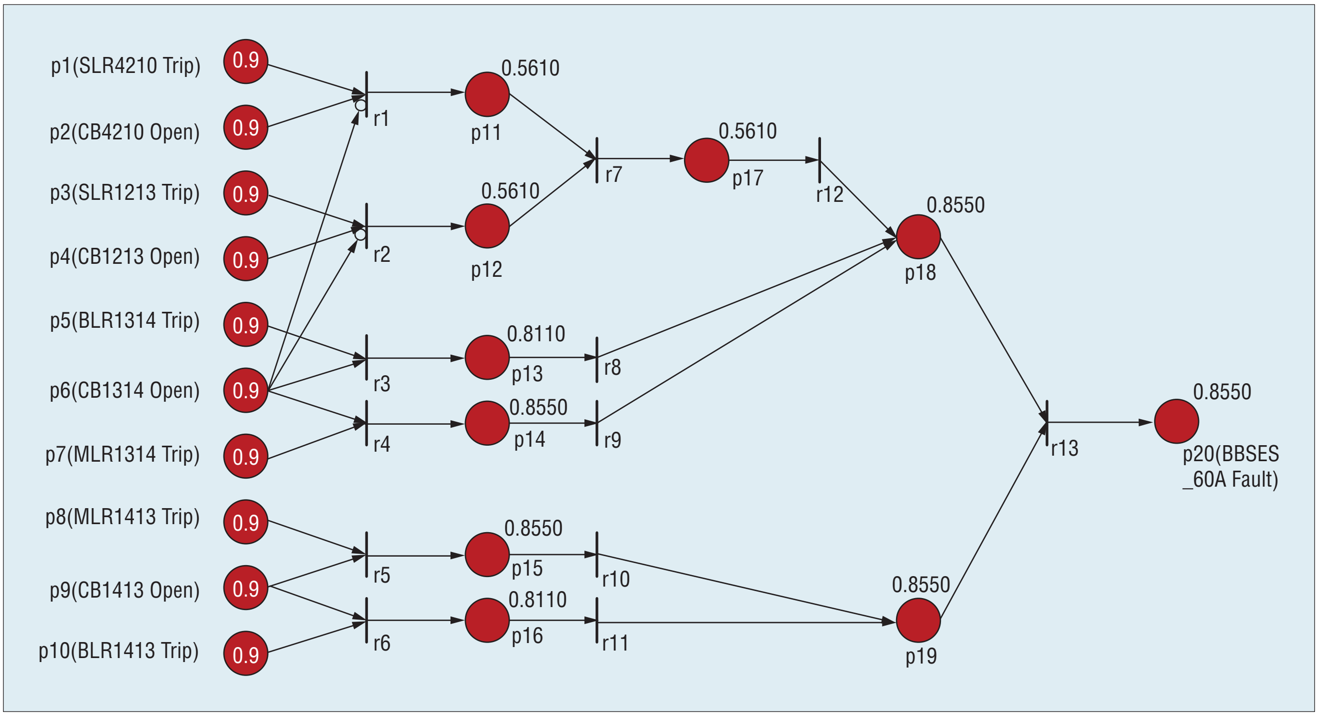

Figure 8. Fuzzy-reasoning Petri net (FRPN) model analysis procedure for Line BBSES_60A_with_assumed_relay_data. Circuit breakers CB4210, CB4220, CB4160, and CB4920 were detected, so line BBSES_60A is faulted, and its truth value is 0.8550.

for electricity market use. For market participants, the competition result is unknown because there is no way to predict who will win. However, the one who has been notified by the IEAP in advance and changes their strategies accordingly will have substantial advantages.

In practice, the weight factors need to be assigned through collaboration with the experienced operators and maintenance staff, who are familiar with the importance and reliability of each component in the power system. We can also add more market indices in the summary report for the benefit of the whole system and market participants, such as financial transmission rights (FTRs).

To reduce the operators' burden, the ultimate screen in the control center will not show any redundant numerical truth degree factors or alarm messages. Instead, a final fault-analysis result and some possible recommendations will pop up to help the operators make a quick decision. However, the intermediate cause-effect analysis procedure is available any time the operators are ready to monitor it.

THE AUTHORS

Yufan Guan is a doctoral student at Texas A&M University. His research interests include alarm processing, substation automation, and artificial intelligence applications in power systems. Guan has a BS in electrical engineering from Zhejiang University, Hangzhou, China. Contact him at carling@tamu.edu.

Mladen Kezunovic is the Eugene E. Webb Professor and site director of the Power Engineering Research Center (PSerc) and deputy director of Plug-In Hybrid Electric Vehicle/Battery Electric Vehicle (PHEV/BEV) Transportation and Electricity Convergence (TEC) at Texas A&M University. His research interests include digital simulators and simulation methods for relay testing as well as applying intelligent methods to power system monitoring, control, and protection. Kezunovic has a PhD in electrical engineering from the University of Kansas. He is a member of the International Council on Large Electric Systems (CIGRE) and is a Registered Professional Engineer in Texas. Contact him at kezunov@ece.tamu.edu.

References

1. H.-P. Chao et al., "Interface Between Engineering and Market Operations in Restructured Electricity Systems," *Proc. IEEE*, vol. 93, no. 11, 2005, pp. 1984–1997.
2. R. Dahlgren, C.-C Liu, and J. Lawarree, "Risk Assessment in Energy Trading," *IEEE Trans. Power Systems*, vol. 18, no. 2, 2002, pp. 503–511.
3. J.W. Stahlhut, G.T. Heydt, and J.B. Cardell, "Power System 'Economic Alarms,'" *IEEE Trans. Power Systems*, vol. 23, no. 2, 2008, pp. 426–433.
4. Z. Vale et al, "SPARSE: An Intelligent Alarm Processor and Operator Assistant for Portuguese Substations Control

Table 3. 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	$12,000/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 2 MW
Generation 1	300 MW
Generation 2	400 MW
Total generation cost	$12,000/hour
Suggested actions	
Option 1	*Increase PG1 and decrease PG2*
Fault detected?	Line 3-5 is out
Any thermal violations?	No
Generation 1	330 MW
Generation 2	370 MW
Total generation cost	$12,150/hour
Changes in total generation cost	Increased by $150/hour
Option 2	*Take Line 3-4-1 out*
Fault detected?	Line 3-5 is out
Any thermal violations?	No
Generation 1	400 MW
Generation 2	300 MW
Total Generation Cost	$12,000/hour
Changes in total generation cost	No

Table 4. Comparison between conventional alarm processors and the IEAP.

Criteria	Conventional alarm processors	Intelligent Economic Alarm Processor
Inputs	Generation alarms, line alarms, and so on	Electrical grid alarms and power market schedules and trends (such as local marginal prices)
Outputs	Alarm priorities, decisions, and recommendations	System operation alarms and solutions and the impact on the electricity market
Time	Time consuming	Within seconds
Accuracy	Not applied	Very certain
Target audience	Operators	Operators and all market participants

Centers," *IEEE Intelligent Systems*, vol. 12, no. 3, 1997, pp. 86–93.
5. P. Kadar, "A Complex Method for Failure Analysis," *Proc. 2nd Symp. Expert Systems Application to Power Systems*, 1989, pp. 283–289.
6. L. Faria et al., "Training Control Centers' Operators in Incident Diagnosis and Power Restoration Using Intelligent Tutoring Systems," *IEEE Trans. Learning Technologies*, vol. 2, no. 2, 2009, pp. 135–147.
7. Y.F. Guan and M. Kezunovic, "Implementing Intelligent Techniques for the Advanced Alarm Processing," *Proc. 15th Int'l Conf. Intelligent System Applications to Power Systems*, IEEE Press, 2009, pp. 1–6.
8. X. Luo and M. Kezunovic, "Implementing Fuzzy Reasoning Petri-Nets for Fault Section Estimation," *IEEE Trans. Power Systems*, vol. 1, no. 1, 2006, pp. 1–10.
9. Y.H. Song, X. Wang, and J.Z. Liu, "Operation of Market-Oriented Power Systems;" www.springer.com/978-1-85233-670-7.
10. M. Pfau-Wagenbauer and W. Nejdl, "Integrating Model-Based and Heuristic Features in a Real-Time Expert System," *IEEE Intelligent Systems*, vol. 8, no. 4, 1993, pp. 12–18.
11. K.W. Hedman, "Flexible Transmission in the Smart Grid," doctoral dissertation, Dept. of Industrial Eng. and Operation Research, Univ. of California, Berkeley, 2010.