Optimization-based Strategies towards a Self-healing Smart Grid

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***Abstract*—Self-healing is a critical and desirable feature for electric power systems. Following an outage, it is critical to restore system back to a normal operation condition as efficiently as possible. The advanced decision support tools are needed to assist system operators to restore a grid from major outages efficiently and safely and enhance the resilience of a smart grid. In this paper, optimization modules are developed for generation, transmission and distribution system restoration. These developed modules provide an automated and "best adaptive strategy" procedure for power system restoration. The IEEE 39-bus test system is used to validate the proposed strategy. Simulation results demonstrate that the proposed optimization-based power system restoration strategy is highly efficient. Future developments are discussed for extensive testing, implementation planning, and actual implementation in a real-time operational environment.**

***Index Terms*—Self-healing, Power System Restoration, Multiple Optimization Modules, Blackstart Capability**

I. Introduction

Power system reliability has been impacted by recent catastrophic and cascading failures throughout the world. The Aug. 14, 2003, blackout in USA and Canada affected an area with an estimated 50 million people and 61,800 MW of load. The duration of the outage is about two days, and the estimated of total costs ranges between $4 billion and $10 billion [1]. Smart grid technologies are expected to minimize the consequence of widespread blackouts and dramatically reduce the cost of interruptions [2]. Power system recovery or restoration is increasingly important to enable the self-healing grid to become a reality and bring benefits to energy consumers and suppliers.

Following an outage of the system, the restoration process returns the system to a normal operating condition. Power system restoration is a complex problem including the assessment of system conditions, generation unit start-up, transmission network energization, load pickup and electrical islands synchronization [3]. At present, power system operators are guided by off-line restoration plans developed for selected scenarios of contingencies, equipment outages, and available resources to manually perform system restoration actions [4]. Facing extreme emergencies threatening the system stability, they need to be aware of the situation and adapt to the changing system conditions during system restoration [5].

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In the literature, several approaches and analytical tools have been proposed to better support dispatchers in the decision making process. The knowledge-based systems (KBS) restoration tool is developed to integrate both dispatchers' knowledge and computational algorithms for system analysis [6-7]. There are simulation-based training tools; for example, Electric *Power Research Institute (EPRI)-Operator Training Simulator (OTS)* and *PowerSimulator*, offer training on system restoration for control center dispatchers. Moreover, optimization approaches, such as Lagrangian Relaxation [8], dynamic programming [9] and Mixed Integer Linear Programming (MILP) [5], haven been utilized to develop fast solution methodology with optimality guaranteed.

In the Power Systems Engineering Research Center (PSERC) project involving several U.S. universities and energy companies, optimization modules are developed for generation, transmission and distribution system restoration. With additional development work, these modules can be used in an on-line decision support tool, which reduces restoration time while maintaining system integrity, and ultimately, leads to lower outage costs for blackout events.

In this paper, the design of multiple optimization modules strategy is introduced first, including *Generation Capability Optimization Module* (*GCOM*), *Transmission Path Search Module* (*TPSM*), *Constraint Checking Module* (*CCM*) and *Strategy Module*. The IEEE 39-bus test system is used to validate the proposed strategy. Then other restoration strategies, such as Generic Restoration Milestones (GRMs)-based strategy, and its application in blackstart capability assessment are discussed, followed by the future development.

II. Multiple Optimization Modules Strategy

A. System Restoration Procedure

By designing computational modules for the generation, transmission and distribution subsystems, a comprehensive strategy is developed to facilitate system restoration. The modules can be used in an on-line decision support tool, which can help system operators adapt to changing system conditions that occur during an actual restoration. The primary modules in Fig. 1 [5] are generation capability maximization, transmission path search, distribution restoration and constraint checking. These modules interact with each other to develop a feasible plan that incorporates generation, transmission, distribution and load constraints.

Specifically, *GCOM* first provides an optimal generator starting sequence, and *TPSM* identifies the paths for the cranking sequence from *GCOM* and energizes the transmission network. Then *Distribution Restoration*

Module (*DRM*) provides the load pickup sequence to maintain the system stability and minimize the unserved load. The sequences from *GCOM* and *DRM* and the transmission paths from *TPSM* are checked by *CCM* using power system simulation software tools to ensure that various constraints are met. They interact with each other by receiving the input from and passing the output to other modules. Eventually, this will lead to the successful restoration of a power system.

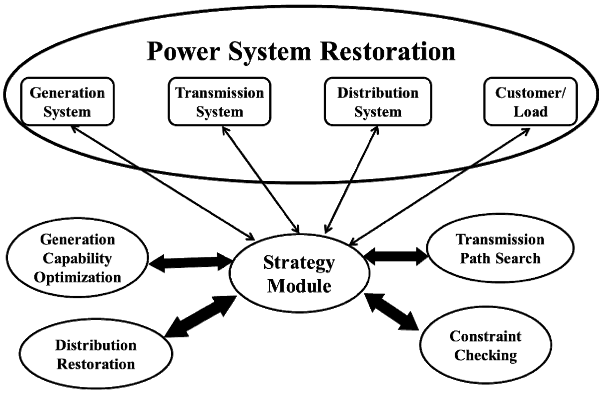

Fig. 1. Power system restoration strategy

If there is a constraint violation, the corresponding constraint will be added back to specific module and the restoration plan will be updated accordingly. For example, if the transmission path is unavailable, say due to a fault on a line, which causes a unit in the starting sequence to become unavailable, then the corresponding constraint will be added to *GCOM* to determine a new cranking sequence so that the unit can be cranked by other units that are available through another path. For another example, if one generating unit cannot be started, say, due to a generator transient stability limits violation, then *GCOM* will update the starting time of this generator, which will be delayed until after the planned starting.

B. Generation Capability Optimization Module

During system restoration, generation availability is fundamental for all stages of system restoration. According to the start-up power requirement, generating units can be divided into two groups: blackstart (BS) generators and non-blackstart (NBS) generators. A BS generator, e.g., hydro or combustion turbine units, can be started with its own resources, while NBS generators, such as steam turbine units, require cranking power from outside [5]. Available BS units must provide cranking power to NBS units in such a way that the overall available generation capability is maximized. Therefore, the generator start-up strategy is important to the system restoration plan. The corresponding generation optimization problem is combinatorial with complex practical constraints that vary with time, and it needs modern optimization techniques to provide efficient computer solutions.

Objective function: The objective is to maximize the overall system MW generation capability during a specified system restoration period. The system generation capability is defined as the sum of MW generation capabilities over all units in the power system minus the start-up power requirements.

Constraints: NBS generators may have different physical characteristics and requirements. If a NBS unit does not start within the corresponding "critical maximum time interval", the unit will become unavailable after a considerable time delay. On the other hand, a NBS unit with the "critical minimum time interval" constraint is not ready to receive cranking power until after this time interval. Moreover, all NBS generators have their start-up power requirements. These units can only be started when the system can supply sufficient start-up power. Also, voltage and reactive power have to be carefully considered during the development of System Restoration Black Start Plan, which can be monitored and checked by the *CCM.*

Method 1: Taking advantage of the quasiconcave property of the generation ramping curves, a "Two-Step" method is proposed to solve the optimization problem. For each generator, the generation capability curve is divided into two segments. One segment is from the origin to the "corner" point where the generator begins to ramp up, and the other segment is from the corner point to point when all generators have been started. Then time horizon is divided into several time periods, and in each time period, generators using either first or second segment of generation capability curves. The quasiconcave optimization problem is converted into concave optimization problem, which optimality is guaranteed in each time period. Then the generator start-up sequencing problem can be formulated as a Mixed Integer Quadratically Constrained Program (MIQCP) problem. The detailed formulation and solution methodology can be referred to [10].

Method 2: By introducing new binary, integer and linear decision variables, the generator start-up sequencing is formulated as MILP problem based on a 4-step transformation. The linear formulation leads to an optimal solution to this important problem that clearly outperforms heuristic or enumerative techniques in quality of solutions or computational speed. The detailed formulation and algorithm can be referred to [5].

Strategy: In the above formulation, it is assumed that the scenario is a complete shutdown and each generator can be started with the cranking power delivered through the transmission network. During system restoration, it is likely that some generation units or transmission paths become unavailable or only partial blackstart. To relieve these assumptions, the generator start-up strategy is proposed, as shown in Fig. 2.

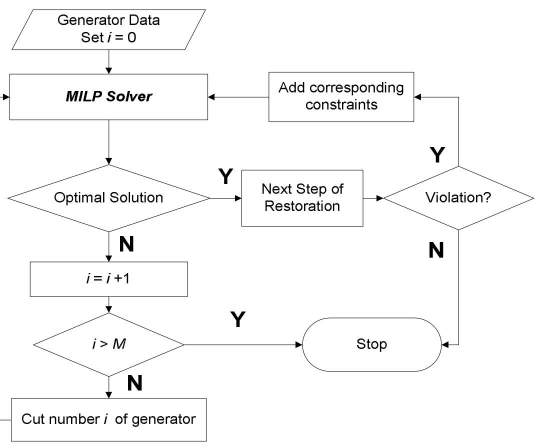

Fig. 2 Flow chart of Generation Capability Optimization Module

Then *GCOM* provides an initial starting sequence of all BS and NBS units. If there is any violations while other restoration actions are taken, such as transmission path search or constraint checking, add the corresponding constraint and go back to calculate the new start-up sequence. The module is able to update system MW generation capability as the restoration process progresses [5].

C. Transmission Path Search Module

After generator start-up, available transmission path needs to be identified to transfer cranking power and build the transmission network. The shortest transmission path search is important to minimize the cost of interruptions and prepare for the next-step restoration actions.

Objective: Find the shortest path between two busbars with the minimum number of operations of circuit breakers (CBs).

Method: Through the CB connected to the energized busbar, find the de-energized busbar, continue iterations until the target busbar is found. It is a breadth-first search.

1) Correlation Matrix of CB and Busbar/line

The correlation matrix is created according to the following two criteria:

- Each row represents one CB, and each column represents one busbar/line
- For each CB, it connects two busbars/lines.

If there is a connection, the correlation coefficient is 1; otherwise, it is 0. In each row, only two numbers are nonzero. It is a highly sparse matrix.

2) Shortest Path Solver

Beginning from the energized busbar, open CBs connected to energized busbars are candidates. By the *availability check*, other busbars connected to these candidate CBs are chosen as available busbars. Then it is decided, by *feasibility check*, whether or not to close these candidate CBs to energize or synchronize available busbars from energized busbars. Repeat these two checks until all busbars are energized, as shown in Fig. 3. The detailed algorithm can be referred to [4].

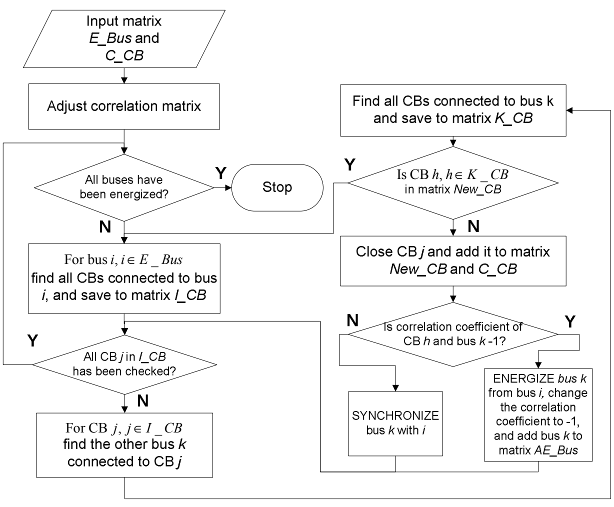

Fig. 3 Flow chart of Transmission Path Search Module

The advantage of the proposed shortest path solver is to consider Generic Restoration Actions (GRAs) proposed in [3] to generalize various restoration steps in different system restoration strategies. The time to take restoration actions should be considered to achieve more accurate search and establishment of transmission paths. The (fictitious) time to complete each GRA is given in Table I [7].

TABLE I
TIME TO COMPLETE RESTORATIVE ACTIONS

Generic Restoration Action (GRA)	Time (hr)
Restart BSU	0:15
Energize Busbar from BSU/Busbar/Line	0:05
Connect Tie Line	0:25
Crank a NBSU from a Busbar	0:15
Synchronize between Busbar/Line	0:20
Pick up Load	0:10

In reality, various switching times will need to be incorporated in order to estimate more accurate restoration time. Another power transfer distribution factors (PTDFs)-based transmission path selection approach for large-scale power systems is developed by team members in the same PSERC project [11].

D. Constraint Checking Module

Based on the steady state analysis and power flow calculation tools, *CCM* is performed with the following two functions: pick up load according to generation capability to maintain system frequency and balance reactive power to control bus voltage and branch MVA, as shown in Fig. 4.

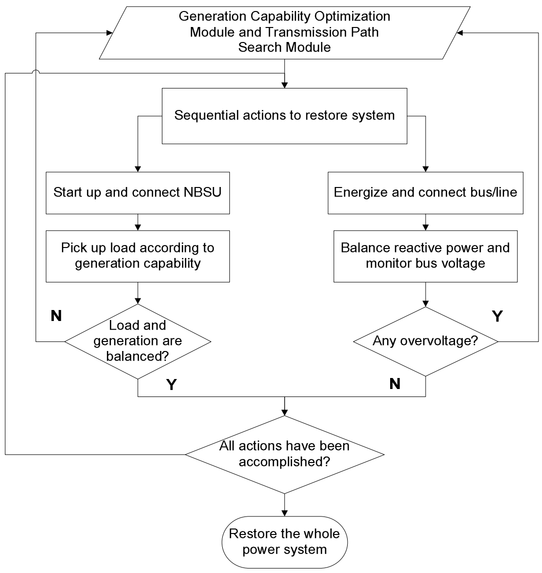

Fig. 4 Flow chart of Constraint Checking Module

Considering blackstart constraints, generation/load balance constraints and voltage stability constraints, another ordered binary decision diagram (OBDD) -based system sectionalizing method is developed by team members in the same PSERC project [12]. This method is able to determine the proper splitting points to sectionalize the entire blackout area into several subsystems for parallel restoration to speed up the restoration process.

E. Strategy Module

Three developed modules of *GCOM*, *TPSM* and *CCM* are linked and coordinated by the *Strategy Module* to provide an automated and "best adaptive strategy" procedure for power system restoration. These modules together identify restoration decisions that reduce restoration time while maintaining system integrity, and ultimately will lead to lower outage costs for blackout events.

Step 1: Input the generator starting sequence from *GCOM*, and read system topology data to form the correlation matrix of CB and Busbar/line.

Step 2: Start blackstart-unit (BSU).

Step 3: Energize the Busbar connected with BSU.

Step 4: According to the generator starting sequence, find the path from BSU to non-blackstart-unit (NBSU) by using *shortest path solver*. If there is no available transmission line, go back to *GCOM* and find new generator starting sequence. Save the sequence to *Busbar_Path* and *CircuitBreaker_Path*.

Step 5: Provide cranking power along the path to start NBSU and synchronize NBSU with its connected busbar. If any violation reported from *CCM*, go back to *GCOM* and find new sequence, and then go to *shortest path solver* to get a new path.

Step 6: Build the entire transmission system by *TPSM*. If any violation reported from *CCM*, go back to *shortest path solver* to get a new path.

Step 7: *DRM* to restore distribution system and restore the whole power system.

The flow chart of *Strategy Module* is shown as following:

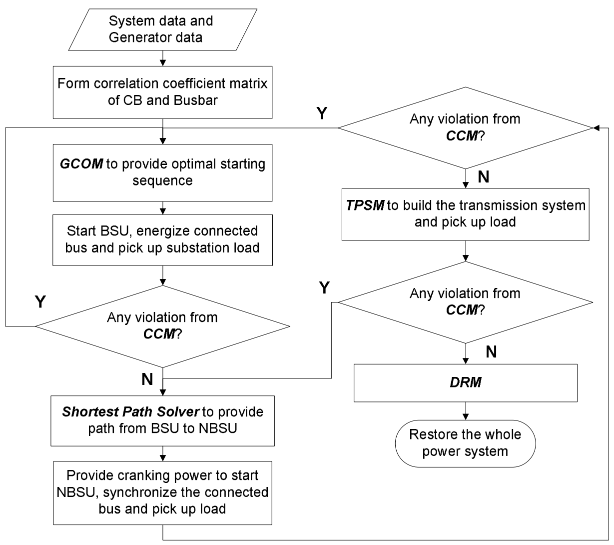

Fig. 5 Flow chart of Strategy Module

In the step 7 of *Strategy Module*, *DRM* is developed by team members in the same PSERC project using optimization algorithms, in particular, the Lagrangian relaxation method and Binary Integer Programming [4]. This operator permissive *DRM* tool is expected to run in parallel with the restoration process, with each run using updated values for loads and expected generation in order for the tool to use the best available information during the entire process.

III. Numerical Results

A. Case of PJM 5-Bus System

The PJM 5-Bus System is used for illustration of the proposed model and solution methodology, as shown in Fig. 6. There are 4 generators, 5 buses and 6 lines. The generator and transmission system information is given in Table II and Table III.

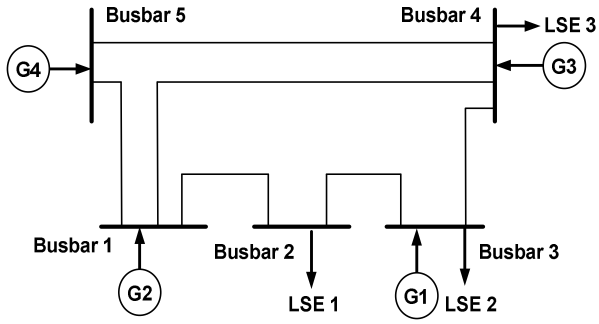

Fig. 6 PJM 5-bus system

TABLE II
GENERATOR CHARACTERISTICS

	Gen. 1	Gen. 2	Gen. 3	Gen. 4
Time to Start Up and Parallel with System (p.u.)	2	1	2	1
Critical Min. Time Interval (p.u.)	N/A	5	N/A	N/A
Critical Max. Time Interval (p.u.)	5	N/A	4	N/A
Ramping Rate (MW/p.u.)	2	4	4	1
Start-up Power Requirement (MW)	1	1	2	
Max. generation output (MW)	8	12	20	3
Connected Bus	3	1	4	5

TABLE III
DATA OF TRANSMISSION SYSTEM

Branch	From Bus	To Bus	Reactance X (p.u.)	Limit (p.u.)
1	1	2	0.0281	2.50
2	2	3	0.0108	3.5
3	3	4	0.0297	2.4
4	4	5	0.0297	2.4
5	5	1	0.0064	4
6	1	4	0.0304	1.5

The scenario of a complete shutdown is assumed. Unit G4 is a BSU, while G1 – G3 are NBSUs. The restoration actions to restore the whole system are shown in Table IV.

TABLE IV
RESTORATION ACTIONS

Time (hr)	Action
t=0:00	Start G4
t=0:10	N/A
t=0:20	Energized Bus 5
t=0:30	Energized Bus4, Line 4
t=0:40	Energized Bus1, Line 5, Line 6, Start G3
t=0:50	Energized Bus 2, Line 1, Start G2
t=1:00	Energized Bus3, Line 2, Line 3
t=1:10	Start G1

B. Case Study of IEEE 39-Bus System

The IEEE 39-Bus system, as shown in Fig. 7, is used for illustration of *GCOM*, *TPSM* and *CCM*, and their interaction with *Strategy Module*.

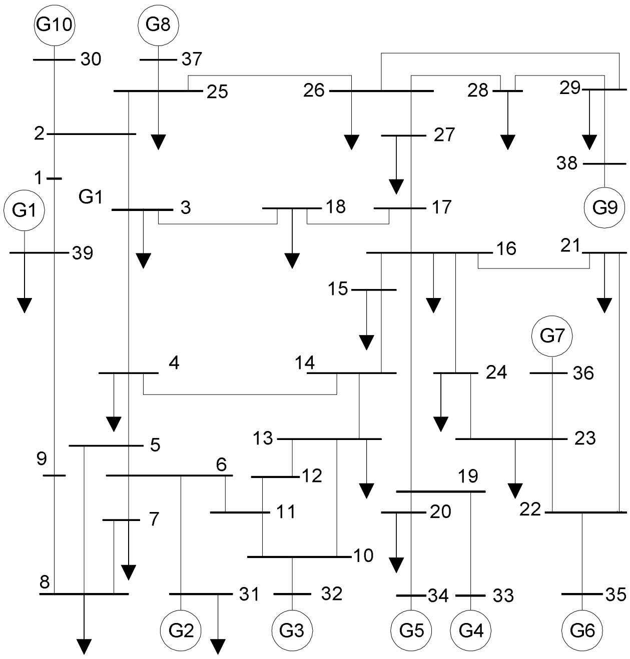

Fig. 7 IEEE 39-bus system topology

Generator data and transmission system data can be referred in [11]. There are 10 generators and 39 buses. The scenario of a complete shutdown is assumed. Unit G10 is a BSU while G1 – G9 are NBSUs. The restoration actions are checked and updated every 10 minutes.

Step 1: *GCOM* provides the optimal starting time for all NBS generation units, as shown in Table V.

TABLE V
GENERATOR STARTING TIME

Gen.	1	2	3	4	5	6	7	8	9
Starting Time (hr)	0:60	1:30	1:40	1:40	1:50	1:50	1:50	1:00	1:40

Step 2: *TPSM* finds the shortest path to transfer cranking power to start up NBSU and establish the transmission network. The restoration actions to energize each bus or line are shown as following:

TABLE VI
RESTORATION ACTIONS

Time (hr)	Start Gen	Energize Bus	Energize Line
0:00	G10	N/A	N/A
0:10	N/A	N/A	N/A
0:20	N/A	30	N/A
0:30	N/A	2	1
0:40	N/A	1,3,25	2,6,8
0:50	N/A	4,18,37,39	3,5,9,11
1:00	G1,G8	5,14,17	10,12,13
1:10	N/A	6,8,13,15, 16,26,27	7,14,17,31, 32,34,35
1:20	N/A	10,11,12,21, 24,28,29,31	18,19,20,22,25, 27,28,36,38,43
1:30	G2	7,20,22,23, 32,33,38	15,16,24,30, 37,39,41,44
1:40	G3,G4, G9	34,35,36	40,42,46
1:50	G5,G6,G7	N/A	N/A

Step 3: Table VII provides the updated actions provided by *CCM*. By the cooperation of three modules, the entire system was successfully restored.

TABLE VII
UPDATED RESTORATION ACTIONS BY *CCM*

Time (hr)	Bus	Violation	Action
0:20	2	Overvoltage	Postpone paralleling G10
0:30	1,2,3,25	Overvoltage	Postpone paralleling G10
0:40	N/A	N/A	Pick up load at Bus 2,4,18, 25,26,29 and connect G10
1:10	26,29	Overvoltage	Energize Bus 27
1:10	29,38	Overvoltage	Postpone paralleling G8
1:20	28,39	Overvoltage	Pick up load at Bus 28,29
1:30	N/A	N/A	Energize Bus 38
1:40	N/A	N/A	Start G9

IV. OTHER STRATEGIES AND FUTURE DEVELOPMENT

A. Generic Restoration Milestones-based Strategy

A decision support system for establishing and evaluating system restoration strategies with the newly proposed concept of Generic Restoration Milestones has been successfully developed [13]. While different system restoration strategies share some characteristics, GRMs generalize power system restoration actions and provide a general toolbox for system restoration strategy establishment. After analyzing system conditions, the system operators or system restoration planners can select a series of Milestones for this toolbox, and establish a restoration planning strategy by combining GRMs.

Utilizing the concept of GRMs, the System Restoration Navigator (SRN) is developed to serve as a decision support tool for evaluating system restoration strategies [14]. The SRN is able to establish a sequence of generating units starting, transmission network energization and load pick-up for system restoration plan following a complete or partial outage subject to steady-state constraints.

B. Blackstart Capability Assessment

Blackstart capability assessment is important for system planners to prepare the power system restoration (PSR) plan. After a partial or complete system blackout, BS resources initiate the process of system restoration and load recovery to return the system to a normal operating condition. To achieve a faster restoration process, installing new BS generators can be beneficial in accelerating system restoration. After new BS generating units are installed, system restoration steps, such as generator startup sequence, transmission path, and load pick-up sequence, will change. However, there is a point where benefits of additional BS capabilities will not increase further. Therefore, power systems have to update the PSR plan and quantify the benefit based on appropriate criteria [15].

In [16], a decision support tool using GRMs-based strategy is utilized to provide a quantitative way for assessing the optimal installation location and amount of BS capability. Based on the proposed criteria, the benefit from additional BS capability is quantified in terms of system restoration time. . It is shown that power systems can benefit from new BS generators to reduce the restoration time. However, there is a threshold beyond which system restoration time cannot be further reduced from additional BS capability. Economic considerations should be taken into account when assessing additional BS capabilities.

C. Future Development

More practical constraints need to be incorporated into the system restoration decision support tool, such as switching transients, generator transient stability limits, the under-excitation capability of generators, load rejection and low frequency isolation scheme. It can be accomplished by integrating the developed module with power system simulation software tools. To provide an adaptive decision support tool for power system restoration, the data and implementation issues for an on-line operational environment need to be investigated in the future.

More functional modules can be developed utilizing Generic Restoration Milestones. Then for both real-time and PSR strategy planning, the tool can provide dispatchers the updated information of system condition in the form of available generation capability, the amount of load that can be picked up, and the duration of total system restoration. Then dispatchers can select the restoration plan or strategy according to the priority of their own system restoration.

V. Conclusions

An optimization-based power system restoration strategy is proposed in this paper. By designing computational modules for the generation, transmission and distribution system restoration, this decision support strategy is able to help system operators adapt to changing system conditions and reduce restoration time while maintaining system integrity. With future development and implementation, the effective system restoration strategy will lead an important step toward the self-healing smart gird.

VI. Disclaimer

This study reflects the views of the authors and not the views of their institutions or affiliations.

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VIII. Biographies

Wei Sun (M’08) received his Ph.D. degree from Iowa State University. He is currently a power system engineer with Alstom Grid, Redmond, WA, USA. His research interests include power system restoration, carbon dioxide emission regulation, generation scheduling, and optimization methodologies applied to power system problems.

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