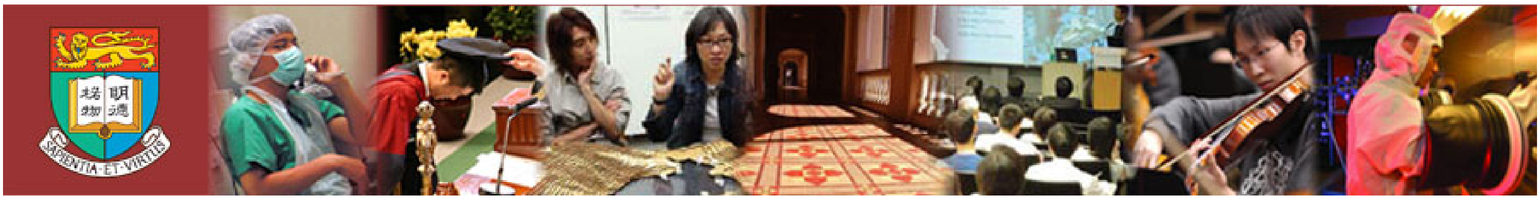

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Constructing Power System Restoration Strategies

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Abstract

System restoration is an integral part of the overall defense system against catastrophic outages. The nature of system restoration problem involves status assessment, optimization of generation capability and load pickup. The optimization problem needs to take into numerous practical considerations and, therefore, it cannot be formulated as one single optimization problem. The other critical consideration for the development of decision support tools is its generality, i.e., the tools should be portable from a system to another with minimal customization. This presentation will provide a comprehensive methodology for construction of system restoration strategies. The strategy adopted by each power system differs, depending on the system characteristics and policies. A new method based on the concept of "generic restoration milestones" and "generic restoration actions" has been developed. A specific restoration strategy can be synthesized by a combination of the milestones and actions based on the actual system conditions. The decision support tool is expected to reduce the restoration time, thereby improving the system reliability.

***Index Terms*—Power system restoration, generic restoration milestones, generic restoration actions**

I. INTRODUCTION

Power system restoration is recognized as one of the most important tasks for electric power grids. With interconnection of the power grids, blackouts can make a significant impact. It is reported that the impact of a blackout increases exponentially with the duration of system restoration [1, 2]. Hence, system reliability depends heavily on the efficiency of system restoration. Recent blackout events call for greater attention to be paid to system restoration methodologies and their associated decision support tools.

To improve the reliability of a power system, it is important to develop a decision support tool to assist power grids in system restoration planning and, ultimately, in on-line system restoration. Unfortunately, it is largely a manual task at this time and, few decision support tools are available to dispatchers and restoration planners. At present, restoration plans are developed with basic simulation tools, such as power flow, dynamics [3-5], and electromagnetic transients [6, 7]. These plans developed off line are then used as guidelines for dispatchers in an on-line environment [8, 9]. Based on the guidelines established off line, dispatchers develop the strategy based on characteristics of the outage scenario and available resources.

Restoration strategies are closely related to the specific system characteristics [10, 11]. Since one system's situation does not conform readily to the situations of another system, restoration strategies cannot be generalized easily. Another difficulty in development of a restoration plan is the unavailability of efficient optimization tools. Mathematically, the restoration problem can be formulated as a series of optimization problems. Multi-objective and combinatorial optimization problems with numerous practical considerations are involved. Solving these optimization problems within limited computing time is a difficult task.

The purpose of this paper is to provide a conceptually computational methodology for construction of system restoration strategies. A new method based on the concept of "generic restoration milestones (GRMs)" and "generic restoration actions (GRAs)" has been developed for large interconnected power grids. A specific restoration strategy can be synthesized by a combination of the milestones and actions based on the actual system conditions. A different combination leads to a different strategy option. The decision support tool is expected to reduce the restoration time, thereby improving the system reliability.

II. GENERAL PHILOSOPHIES OF RESTORATION

A. Challenges of Restoration Strategies

As a result of cascading events, even a strong system can become vulnerable and evolve into a catastrophic outage. To increase the robustness of a power system, a wide area protection and control system, such as the Strategic Power Infrastructure Defense system [12], is an important tool. To avoid a cascading failure, real-time sensing and communication, failure analysis, vulnerability assessment, and self-healing control are proposed as a wide area defense system. Power system restoration is an important part of self-healing control within the overall defense system.

The system restoration procedure involves assessment of the system status, optimization of generation capabilities and load pickup. Generally, there are two basic issues in the development of decision support tools for system restoration. The first critical consideration for the development of decision support tools of restoration is its generality, i.e., tools should be portable from a

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system to another with minimal customization. However, a review of the literature and discussions with power system dispatchers from different systems reveal that differences in "strategies" of restoration are closely related to differences in system characteristics. As a result, it is difficult to develop a tool to support power system restoration efforts for a wide range of systems. For the same reason, restoration plans or guidelines are established off line in the context of specific systems.

Another challenge to establish efficient computational tools is the unavailability of efficient optimization tools. The restoration problem needs to take into account numerous practical considerations and, therefore, it cannot be formulated as a single optimization problem. Moreover, these optimization problems are combinatorial in nature. For example, to restart the generating units as quickly as possible, a dynamic programming type of problem has to be solved. To maximize the restored loads, it is formulated as a knapsack problem, which is also NP hard.

B. General Strategies of Restoration

A general procedure for system restoration [3, 13] has three stages, i.e., *Preparation*, *System Restoration*, and *Load Restoration* [13, 14]. In these stages, the basic distinction between the preparation stage and the following stages is that, during the preparation stage, time is critical and some urgent actions must be taken. In the preparation and system restoration stages, load control is a means to maintaining the system stability, whereas in the load restoration stages, load restoration is the primary objective [13, 14].

According to these general stages of restoration, system restoration strategies can be categorized into five general types [14], i.e., *Build-Upward*, *Build-Downward*, *Build-Inward*, *Build-Outward a*nd *Build-Together*, which can be described as follows:

Build-Upward: This strategy is based on defined electrical islands with blackstart capabilities. Islands are resynchronizes after restoration of each island. Major actions involved in this restoration process are startups of blackstart units, cranking of non-blackstart units, restoration of islands, and synchronization of islands.

Build-Downward: By this strategy, the transmission network is re-energized to pool blackstart power first, and then provide cranking power to non-blackstart units. The major steps include startups of blackstart units, energization of the transmission network, and cranking of non-blackstart units.

Build-Inward: For power systems with available tie-line assistance, this strategy can be employed. By assistance of tie-lines, some tie lines are established to restart generating units in some important generation stations. Then, from this basic system and electric power sources, the restoration process proceeds. This strategy is implemented by several actions, such as establishing tie-line, reconnecting transmission networks, and cranking non-blackstart units.

Build-Outward: To re-energize the ring network without assistance from tie-lines, system restoration has to proceed from the ring outward. The major tasks of this strategy are startups of blackstart units, energization of the ring network, and cranking of non-blackstart units.

Build-Together: In this strategy, the skeleton of a transmission network is established in stages to provide cranking power. Non-blackstart units near the load are then restored.

C. Common Issues during Restoration

To establish a restoration plan, the technical feasibility under both steady state and transient operating conditions need to be checked [15]. These technical constraints include:

Active power balance and frequency control. During the restoration process, it is necessary to maintain the system frequency within allowable limits imposed by turbine resonance, system stability, and protection settings. This is accomplished by picking up loads in increments that can be accommodated by the inertia and response of the restored and synchronized system.

Reactive power balance and overvoltage control. To keep system voltages within the allowable region, several actions can be taken during the restoration process: energizing fewer high voltage lines, operating generators at minimum voltage levels, deactivating (over-riding) switched static capacitors, connecting shunt reactors, adjusting transformer taps, and picking up loads with lagging power factors [16].

Switching transient voltage. Energizing equipment during a blackstart may result in overvoltage conditions. Temporary overvoltage can follow switching surges as well. In energizing a large section, the risk of damaging equipment insulation should be considered [6].

Self- excitation. There is the potential for self-excitation if the charging current is high relative to the size of the generating unit. The result can be an uncontrolled rise in voltage and could result in an equipment failure. Self-excitation can also occur from the load end through an inadvertent loss of supply, with the opening of a transmission line or cable at the sending end, leaving the line connected to a large motor or a group of motors.

Cold load pickup. If the load has been de-energized for several hours or more, the inrush current upon re-energizing the load can be as high as eight to ten times of the normal value. This could include lighting, motors, and also thermostatically controlled loads such as air conditioners, refrigerators, freezers, furnaces, and electric hot water heaters [17].

System stability. During the restoration process, to the voltage and rotor angle stability has to be maintained. Generally, angle stability is assessed when more than one generating unit is used in the restoration stages. Otherwise, frequency stability is the main issue in the stability assessment of the plan.

Protective systems and load control. During restoration, the continuing change in power system configurations and their operating conditions might lead to undesired operation of relays. In cases where a dramatic decline in frequency occurs during the restoration process, it is necessary to reduce the amount of load that are connected, which can be accomplished by the application of under frequency load shedding schemes [18].

Partitioning system into islands. To restore the system as quickly as possible, especially for a bulk system, partitioning system into islands is necessary. From the NERC standards, the following criteria should be satisfied [19]:

- Each island must have sufficient blackstart capability;
- Each island should have enough cranking paths to crank non-blackstart units or pick up loads;
- Each island should have the ability to match generation and load to within prescribed frequency limits;
- Each island should have adequate voltage controls to maintain a suitable voltage profile;
- All tie points for subsystems must be capable of synchronization with adjacent subsystems;
- All islands should share information with other islands.

III. GENERIC RESTORATION MILESTONES

A. From GRAs to GRMs

System restoration strategies depend on the system characteristics. However, if one focuses on the tasks of power system restoration, different restoration strategies share some characteristics. Power system restoration involves the following three tasks: unit start-up, network restoration, and load pick-up.

The concept of *Generic Restoration Milestones* (GRMs) is a generalization from actions of power system restoration. A different combination leads to a different strategy option. During system restoration, the following GRMs are needed:

- From Black_Start_Non_Black_Start Building Block
- Form Electrical Island
- Synchronize Electrical Islands
- Establish Transmission Grid
- Serve Load in Area
- Connect with Neighboring System.

A specific restoration strategy can be established by a combination of GRMs based on the system conditions. To implement GRMs, a sequence of *Generic Restoration Actions* (GRAs) can be used. GRAs [14] are actions to be taken during restoration. GRAs include:

- GRA1: start_black_start_unit
- GRA2: find_path
- GRA3: energize_line
- GRA4: pick_up_load
- GRA5: synchronize
- GRA6: connect_tie_line
- GRA7: crank_unit
- GRA8: energize_busbar

Constraints should be met in the implementation of GRAs. A GRM is implemented by a corresponding set of GRAs. It is illustrated as follows.

TABLE I. IMPLEMENTING GRMS WITH GRAS

GRM	GRAs Employed
From Black_Start_Non_Black_Start Building Block	GRA 1, 2, 3, 4, 7, and 8
Form Electrical Island	GRA 1, 2, 3, 4, 7, and 8
Synchronize Electrical Islands	GRA 2, 3, 5, 6, and 8
Establish Transmission Grid	GRA 2, 3, and 8
Serve Load in Area	GRA 2, 3, 4, and 8
Connect with Neighboring System	GRA 2, 3, 5, 6, and 8

B. GRMs for Industry Practice

Various strategy options and constraints are considered in system restoration. GRMs serve as tools in a toolbox. A specific restoration strategy can be established by an appropriate combination of GRMs.

For two example systems, i.e., PJM [10, 20] and Hydro-Quebec [11], the restoration strategies show that the main goal of the restoration plan is to restart generation sources and the transmission grid; load restoration then follows. Since system characteristics are different, the strategies also vary. Generally, there are two categories of systems.

Category 1. For systems with non-blackstart generators, such as PJM, the availability of these units may have critical temporal constraints. In this case, the Build-Upward strategy is employed. In this restoration strategy, the major tasks are startups of blackstart units, cranking and paralleling of non-blackstart units, restoration of islands, and then synchronization of islands.

Category 2. For systems, such as Hydro-Quebec or Bonneville Power Administration, the priority is to establish the transmission network. As a result, the Build-Downward strategy is employed. The major tasks include startups of blackstart units, energization of the network, and load restoration.

Based on the concept of GRMs, for system, such as PJM system, which belongs to *Category 1*, the restoration process can be implemented by the following milestones:

- From Black_Start_Non_Black_Start Building Block
- Establish Transmission Grid
- Form Electrical Island
- Serve Load in Area
- Synchronize Electrical Islands
- Connect with Neighboring System

For the Hydro-Quebec system and Bonneville Power Administration, which belong to *Category 2*, the restoration process can be implemented by:

- Establish Transmission Paths
- Build Electrical Island
- Synchronize Electrical Islands
- Serve Load in Area

IV. SIMULATION RESULTS

A case based on the New England 39-bus system is employed to demonstrate the concepts of GRMs and GRAs for system restoration. This system is shown in Fig. 1.

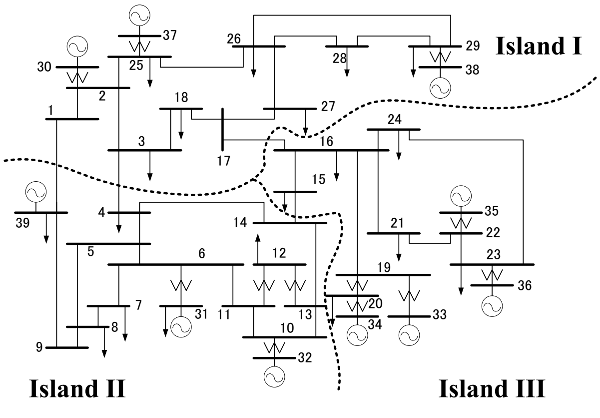

Fig. 1. New England 39-bus system one-line diagram

This system has 10 generating units with a total generation of 7347 MW and 2470 MVar. It has a total load of 6855 MW and 2155 MVar. Suppose there are 3 blackstart units at bus 31, 36, and 37. Based on the criteria of partitioning system into islands that was discussed in section II, this system is divided into 3 islands. As illustrated in Fig. 1. The restoration process of this system involves 5 GRMs. The flow chart of these GRMs is given in Fig. 2.

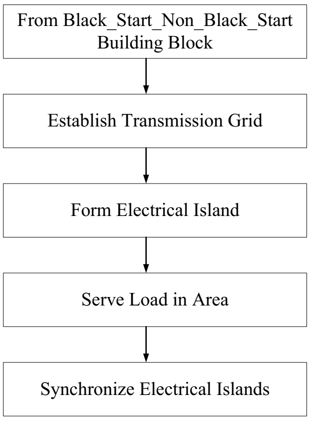

Fig. 2. New England 39-bus system restoration by GRMs

As described in section III, each GRM is implemented by a series of GRAs. Use Island I as an example. The objective of the first GRM, i.e., From Black_Start_Non_Black_Start Building Block, is to restart all of generating units as quickly as possible. To implement this GRM, the following GRAs are employed:

- GRA1: start_black_start_unit
- GRA2: find_path
- GRA3: energize_line
- GRA4: pick_up_load
- GRA7: crank_unit
- GRA8: energize_busbar

In order to implement this GRM as efficiently as possible, the sequence of GRAs should be optimized. During the optimization process, the duration for restarting all generating units is minimized, and all constraints should be satisfied at the implementation of each GRAs. The following constraints may be involved:

- C1: limit of each generating unit
- C2: steady-state overvoltage
- C3: switching transient overvoltage
- C4: voltage stability
- C5: capacity of each line

The sequence of GRAs associated with constraints to implement this GRM is shown in Fig. 3. The constraints during the implementation of each GRA are described within brackets.

GRA1: start black start unit at bus 37
GRA8: energize busbar 37(C3)
GRA2 & GRA3: energize line 37-25 (C1, C2, C3, C5)
GRA8: energize busbar 25 (C3)
GRA4: pick up load at 25 (C1, C2, C4, C5)
GRA2 & GRA3: energize line 25-2(C1, C2, C3, C5)
GRA8: energize busbar 2(C3)
GRA2 & GRA3: energize line 2-30(C1, C2, C3, C5)
GRA8: energize busbar 30 (C3)
GRA7: crank unit at bus 30 (C1, C2, C5)
GRA2 & GRA3: energize line 25-26 (C1, C2, C3, C5)
GRA8: energize busbar 26 (C3)
GRA2 & GRA3: energize line 26-29 (C1, C2, C3, C5)
GRA8: energize busbar 29 (C3)
GRA4: pick up load at 29 (C1,C2, C4, C5)
GRA2 & GRA3: energize line 29-38 (C1, C2, C3, C5)
GRA8: energize busbar 38 (C3)
GRA7: crank unit at bus 38 (C1, C2, C5)

Fig. 3. Implement GRM1 by GRAs

By this sequence, all generating units in Islands I are restarted. It should be noted that picking up loads is only a means to maintaining stability of the island during implementation of GRM1. Similarly, the GRM1 can be facilitated on Island II and III. The total output of each island is illustrated in Fig. 4.

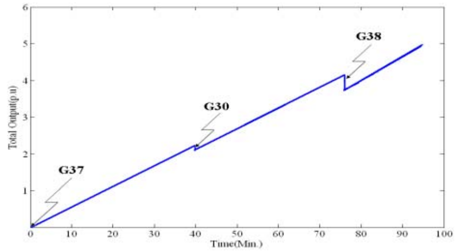

Fig. 4.(a) Total output of Island I

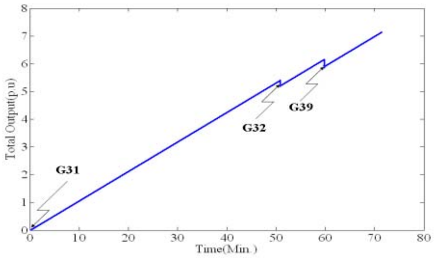

Fig. 4.(b) Total output of Island II

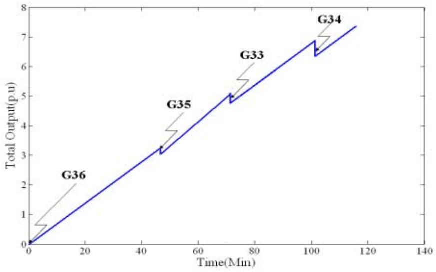

Fig. 4.(c) Total output of Island III

Fig. 4. Total output of each island

In order to restart the system, it requires 4 more GRMs, which are facilitated by the sequences of GRAs as follows. GRM2: Establish Transmission Grid can be implemented by the combination of GRA 2, 3, and 8; GRM3: Form Electrical Island can be implemented by the combination of GRA 1, 2, 3, 4, 7, and 8; GRM4: Serve Loads in Area can be implemented by the combination of GRA 2, 3, 4, and 8. After implementation of these 4 GRMs, three electrical islands are established. The next GRM: Synchronize Electrical Islands, is used to synchronize these islands. For example, to synchronize Island I and II, the following GRAs are used. The constraints during the implementation of each GRA are described within brackets.

GRA2 & GRA3: energize line 2-1(C1, C2, C3, C5)
GRA8: energize busbar 1(C3)
GRA6: connect tie line 1-39 (C1, C2, C3, C5)
GRA5: synchronize Island I and II (C1, C2, C3, C5)

Fig. 5. Implement GRM5 by GRAs

The total output of the entire system before and after synchronization is shown in Fig. 6.

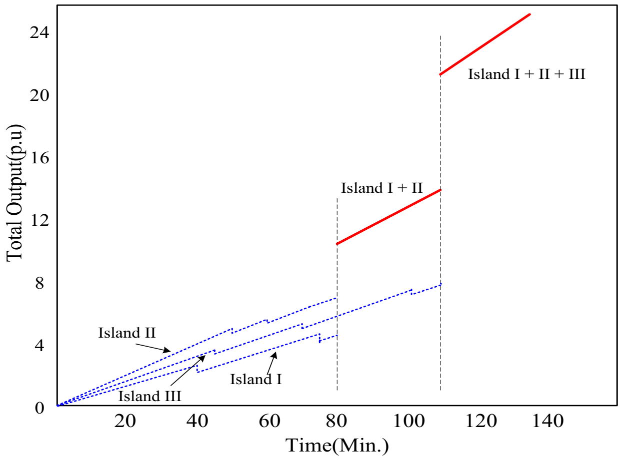

Fig. 6. Total output of the whole system before and after synchronization

Therefore, the entire system is restarted by a sequence of GRMs, which are implemented by the combination of GRAs. Due to the generality of the GRM and GRA concepts, this methodology can be applied to different power systems with some customization.

V. CONCLUSION

Restoration of a power system following a major outage is a complex, stressful and time consuming task. It is important to develop a decision support tool for evaluation of system restoration strategy options. The new concept "generic restoration milestones" has been established in this paper. This concept is abstracted from the actual strategies of power system restoration. Based on the system conditions, a specific restoration strategy can be established by a combination of GRMs. According to the characteristics and policies of a system, each GRM can be implemented by a sequence of "generic restoration actions". All constraints are satisfied during the implementation of these actions, and the sequence of GRAs is optimized for the purpose of GRMs. Simulations based on a standard test system illustrate the generality of the proposed methodologies. A comprehensive methodology for construction of system restoration strategies can be achieved from the proposed concepts.

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