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System Restoration Navigator: A Decision Support Tool for System Restoration

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Abstract—**Power system restoration is well recognized as an important task to reduce the duration of a disturbance that occures in power systems. The complex tasks of emergency recovery require advanced decision support tools to enhance the resilience and, utimately, self-healing capabilities for a smart grid. A piece of software entitled "System Restoration Navigator" (SRN) has been developed based on the Generic Restoration Milestones (GRMs) concept, with the support of EPRI during the last two years. This paper addresses the development and functionality of SRN. Firstly, the basic philosophy of GRMs is introduced. Secondly, the functionality of SRN and integration of SRN with EPRI Operator Training System (OTS) are demonstrated. Thirdly, the Power and Light (PALCO) system is used to illustrate the general restoration plan and concrete restoration actions under a blackout scenario. It is believed that the development of SRN and its integration with OTS is a major step towards the on-line decision-making for system restoration.**

Index Terms—**System restoration, generic restoration milestone, operator training system**

I. INTRODUCTION

Widespread blackouts, such as the 2003 outages in the U.S. and Italy or the 2006 outage in Europe, are powerful reminders of the catastrophic consequences of a few broken links for power grid [1, 2]. Power system restoration is well recognized as an important task to reduce the duration of a disturbance that occurs in power systems. At present, power system recovery or restoration is performed "manually" based on guidelines from a restoration plan prepared off-line, which may not reflect the actual operation condition. It is also time-consuming and highly stressful for system operators. The complex tasks of emergency recovery require advanced decision support tools to enhance the resilience and, ultimately, self-healing capabilities for a smart grid.

EPRI has been working on developing a methodology to implement a decision support system for establishing and evaluating system restoration strategies with the concept of Generic Restoration Milestones (GRMs) [3-7]. The restoration is divided into several typical milestones, which are called GRMs. Each GRM has one main goal and some relevant algorithms to tackle with the technical problems within this milestone. A specific restoration plan may include all, or a subset of GRMs, depending on the characteristics of the targeted system.

As for the restoration planning stage, a software entitled "System Restoration Navigator" (SRN) has been developed with the support of EPRI during the last two years. This software could achieve two essential functions, i.e., evaluation of system restoration procedures, and establishment of a restoration procedure. The practical constraints, such as MVA limits, voltage level, have been included within a restoration procedures evaluation and establishment step by step. Besides, the flexible interactive mechanism can be employed to design a reasonable restoration procedure associated with the planner' expertise.

Since SRN deals with the restoration strategy in a general manner, detailed and concrete dispatch operations should be figured out when implementing a restoration procedure. In real operation environment, more constraints are to be taken into account in term of the dispatches. Furthermore, the restoration dispatch is an emergent task, which requires proficiency and thorough understanding of the specific power grid. Drilling for restoration dispatch under operator training simulator (OTS) environment is essential for power grid operators. The integration of SRN with Operator Training Simulator (OTS) is a major step to bring the decision support tool closer to real-time on-line application. With the implementation of such decision support tools, power grids will be better prepared and equipped for handling extreme events, streamline the communication with all stakeholders, and help preserve and pass on the knowledge to future engineers.

In this paper, the methodology of GRM is briefly introduced. The current functionality of SRN, the integration of SRN with OTS is demonstrated. Several case studies are illustrated.

II. GENERAL PHILOSOPHY OF GENERIC RESTORATION MILESTONE

By studying the practices in industry, it can be found that system restoration strategies are closely related to the systems' characteristics. As a result, it is difficult to develop a generic system restoration decision support tool by the combination of a set of standard 'procedures'. However, if one focuses on the tasks of power system restoration, i.e., the targets of different stages during restoration process, different restoration

strategies share some common characteristics. Therefore, an alternative methodology to establish a generic system restoration decision support tool is to model the restoration process as a combination of targets, or milestones.

The concept of Generic Restoration Milestones (GRMs) provides a toolbox to assist power grid engineers and dispatchers in system restoration planning and, ultimately, in on-line system restoration guidance. After analyzing the system conditions and characteristics of outages, system restoration planners or dispatchers will select a series of GRMs from this toolbox to establish a restoration strategy. Following a power outage, the dispatchers will work with field crews to implement the restoration strategy established by a combination of the GRMs. A comprehensive toolbox based on the concept of GRMs (implemented by highly-efficient algorithms) provides an infrastructure to implement an online decision support tool for system restoration.

To implement the concept of GRMs through computational algorithms, some criteria should be met, such as efficient, generic, adaptive, and flexible. These requirements can be met partly by the concept of GRMs, which provides a generic methodology by transforming the restoration process into a combination of targets. Advanced computational algorithms have been developed to meet these criteria and integrated into SRN.

III. FUNCTIONALITY OF SYSTEM RESTORATION NAVIGATOR

SRN is a software tool that can establish a system restoration plan following a complete or partial outage. Restoration planners can configure the characteristics of generating units, loads, transmission lines, and transformers. SRN generates a restoration plan automatically or under the planners' guidance iteratively. The plan can be displayed on a on-line diagram step by step. The objective of this software is to find a sequence to crank all non-blackstart (NBS) generating units and to pick up all critical loads, which is feasible and has shortest estimated time duration. Operational constraints are taken into consideration, such as capacity limits of various components, power flow constraints, electro-mechanic transient stability, and frequency stability, etc.

Establishing a sequence of generating units and loads is a complex multi-stage optimization problem. The constraints of the power system, such as steady-state and dynamic constraints will be integrated into the search process. To find the solution within a reasonable computational time, the process is decoupled into two interacting sub-problems at each stage.
- Primary problem

Two tasks will be implemented in the primary problem.
(1) A tentative sequence of generating units/loads is established to minimize the time for implementation at this step.
(2) The transmission path is established to implement this sequence. To avoid overvoltage during implementation of the sequence, the charging current of each transmission line is selected as the weight.
- Secondary problem

Two tasks will be implemented in the secondary problem:

(1) Based on the energized block established in the primary problem, the output of each generating unit is found with minimal adjustment time.
(2) If violations cannot be eliminated by adjusting generating units' outputs, some remedial actions, such as pick up dispatchable loads, are implemented.

SRN has some notable functionalities which help planners to find feasible restoration plans.
(1) Various initial states can be defined as a start point of restoration, such as total blackout with single blackstart (BS) unit, total blackout with multiple BS units, partial outage with single survived island, and partial outage with multiple survived islands. For partial outage initial states, a PSS/E raw file can be assigned as the basic power flow snapshot and be imported into SRN.
(2) There are 3 running modes of SRN core module: a) Automatic mode, trying to find a feasible restoration plan with minimum users' interaction. b) Iterative mode, trying to crank one generating unit or critical load assigned by the planner in one step. The process is executed step by step under users' instruction until all Non-BS units and critical loads are restored; c) Advisory mode, performing feasibility check for optional generating units or critical loads within each step.
(3) An efficient time-domain simulation module is integrated to validate the electro-mechanic stability and frequency stability when restoring critical loads or restoring NBS plants auxiliary power supplies.

When SRN is executed in automatic mode, a trace-back mechanism is provided to guarantee that a feasible sequence, if exists, will be found. The basic process of trace-back is as follows. If none of the optional generating units can be cranked with a feasible power flow in some step, the restoration process returns to previous step to crank another optional generating unit. When: (a) all generating units have been cranked, or (b) track back to the last optional generating units of the first step, the calculation will stop. This process is shown in Figure 1.
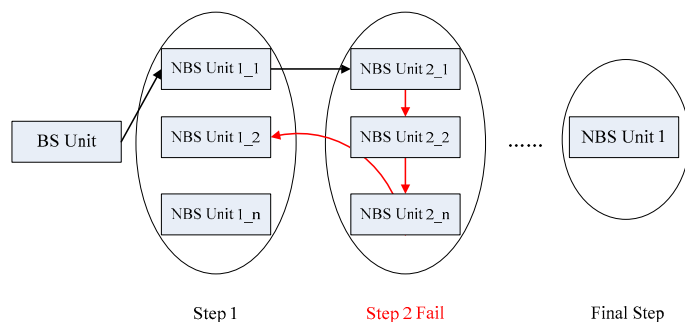

Fig.1. Trace-back mechanism of SRN

IV. INTEGRATION WITH OPERATOR TRAINING SYSTEM

To support the demonstration of the EPRI SRN program, an EPRI OTS based application PowerSimulator was used to integrating SRN.

The integration of SRN and "PowerSimulator" will lead to an EPRI OTS test bed, which is an important step towards an on-line restoration decision support tool.

PowerSimulator with EPRI OTS is designed from the perspective of an operator with graphical display tools to make situational awareness and decision making easier. Operators advance beyond paper drills with the simulator to see the effects or consequences of actions. PowerSimulator can be integrated with custom exercises and training programs to train a wide range of job tasks and skills.

The table below shows some differences between SRN and OTS, from which we can see that the data model in OTS test bed may be more complicated than SRN's part.

TABLE I
DIFFERENCE OF SRN AND OTS TESTBED

	SRN	OTS test bed
Network Model	Mathematic model (node-branch)	Physical model (switch, bus bar, breaker, prime mover, excitation, station…)
State	Single snapshot (base case power flow)	Multiple snapshot (historical data set of measures)
Applications	Power flow, Optimal power flow, Time-domain simulation	State estimation, Power flow, AGC, …
Basic action	Energize line, crank generator, pick up loads…	A series of operations on breakers, switches, generators…(more detailed)

As an off-line decision support tool, SRN uses power flow data as input. A snapshot of power flow of the target power grid is input into SRN with a PSS/E file. After computation for restoration plan, each step of the plan will be generated as a single PSS/E file to log the power flow status after this step is done, as in Figure 2. These PSS/E files can be loaded either in PSS/E for validation or in OTS test bed for integration.

Fig.2. Restoration plan generated by SRN

After the restoration plan is developed by SRN using PSS/E model, the OTS testbed will map system status of each step to the complete system status associated with the physical model

(with bus bars, switches, breakers, etc) and the concrete dispatch actions will then be generated. This is based on the physical- mathematical model mapping between SRN and OTS, as in Figure 3.
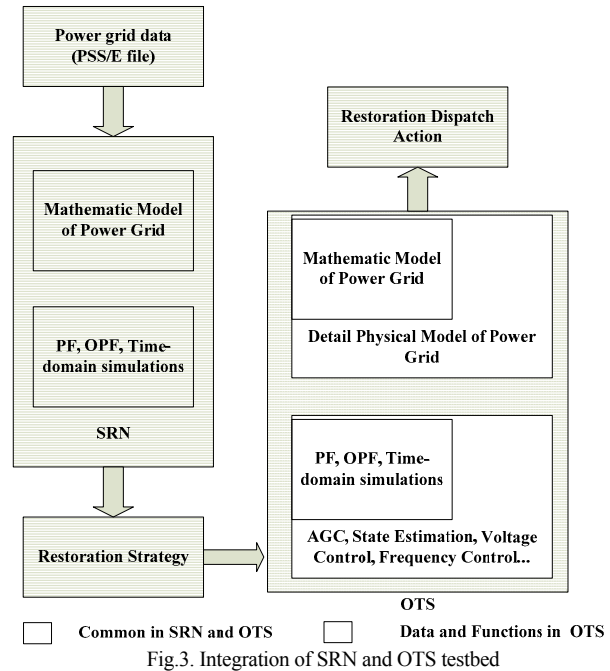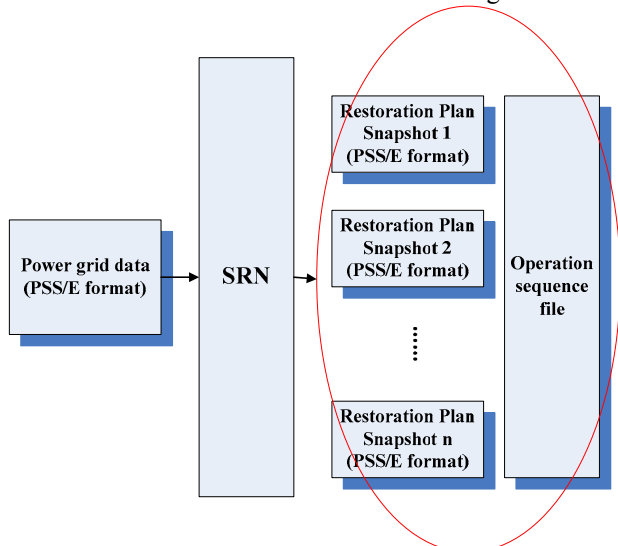

Fig.3. Integration of SRN and OTS testbed

V. CASE STUDY

In this section, a test case is illustrated on how SRN is integrated with OTS test bed.

The OTS test bed is packaged with a generic power system model called PALCO (Power and Light) System model. The PALCO system is complex enough so that trainees can experience all types of operating problems that occur in their own specific systems. The model includes details on various substation breaker configuration including double breaker, breaker and half and single bus single configurations. A PALCO system map is shown below in Figure 4. The substations with generation are shown as circles along with the MW capacity of their units. An example for Crawford station is shown in Figure 5.
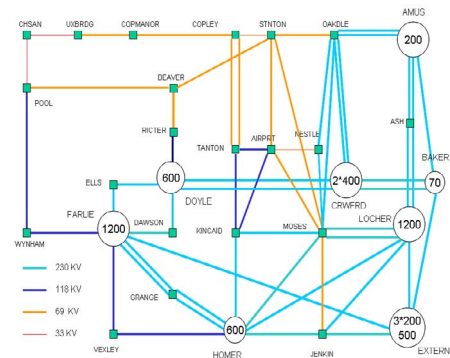

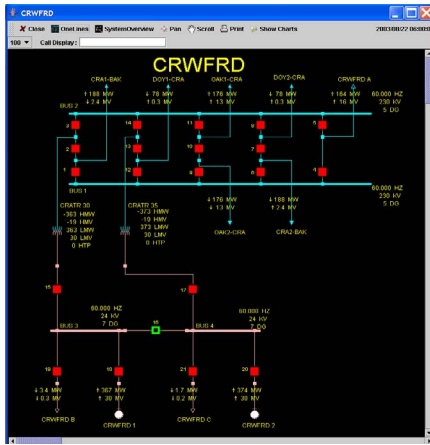Fig.4. One-line Diagram of PALCO in OTS testbed

Fig.5. One-line diagram of CRWFRD station in OTS testbed

A model for PALCO system as a PSSE raw file is imported into SRN. This file can be input to the SNR program to develop restoration procedures. Integration interface is provided for SNR with access to information with the characteristics of the PALCO generating units. A restoration plan is generated in SRN with automatic mode. The restoration plan can be reviewed in one-line diagram of SRN GUI, as in Figure 6. The restoration outline of SRN is shown in Figure 7.

The restoration strategy for PALCO is exported as PSS/E files, which is loaded and checked by EPRI OTS test bed. OTS test bed generates automatically an action file according to these files, as shown in Table II.
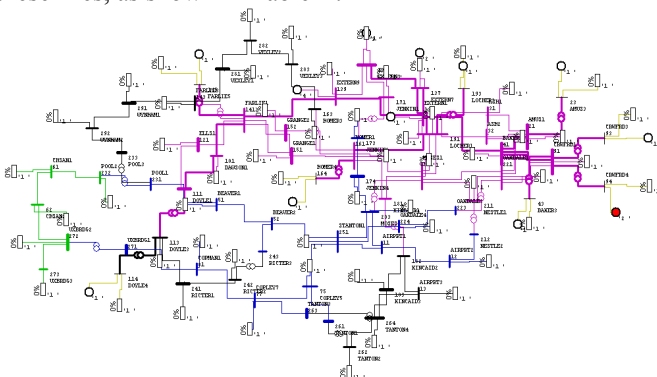

Fig.6. One-line diagram of PALCO in SRN

```
at     0.00 minutes: generator (ID=2) on bus 94 is cranked

   energize transformer 94-91
   energize transformer 91-93

at   100.00 minutes: crank generator (ID=1) on bus 93

   energize line 91-41
   energize line 41-43

at   140.00 minutes: crank generator (ID=1) on bus 43

   energize line 41-21
   energize transformer 21-23

at   175.00 minutes: crank generator (ID=1) on bus 23

   energize line 41-131

at   210.00 minutes: crank generator (ID=1) on bus 131

   energize line 131-137
   energize line 137-133

at   240.00 minutes: crank generator (ID=3) on bus 133
```

Fig.7. Restoration Outline Generated in SRN

TABLE II
RESTORATION DISPATCH ACTION GENERATED BY OTS TEST BED

SRN Step Outline	Station	Equivalent Simulator Actions
at 0.00 minutes: generator (ID=2) on bus 94 is cranked.	CRWFRD	At Crawford substation on Bus 4, Set Crawford Generator to MAN
energize transformer 94-91	CRWFRD	Close breakers to energize transformer between buses 4 and 1
energize transformer 91-93	CRWFRD	Close breakers to energize transformer between buses 3 and 1
at 100.00 minutes: crank generator (ID=1) on bus 93	CRWFRD	At Crawford substation on Bus 3, Set Crawford Generator to MAN
energize line 91-41	to CRWFRD	Close breakers to energize line between Baker Bus 1 and Crawford Bus 1
energize line 41-43	BAKER	Close breakers to energize line between Baker Buses 1 and 3
at 140.00 minutes: crank generator (ID=1) on bus 43	BAKER	At BAKER substation on Bus 3, Set Generator to MAN
……		
energize line 191-161	to LOCHER	Close breakers to energize line between Homer Bus 1 and Locher Bus 1
energize transformer 161-164	HOMER	Close breakers to energize transformer between buses 1 and 4
at 356.18 minutes: crank generator (ID=1) on bus 164	HOMER	At HOMER substation on Bus 4, Set Generator to MAN

VI. CONCLUSION

Effective system restoration is an important step toward a self-healing smart grid. By generalizing industry practice of restoration, an adaptive framework entitled as "Generic Restoration Milestones" has been proposed. Based on the proposed GRM, a software tool entitled "System Restoration Navigator" (SRN) has been developed with the support of EPRI. Tests of SRN on several real power grids have been passed successfully. The integration of SRN with Operator Training System (OTS) illustrated in this paper gives a promising perspective to applying this decision support tool in an on-line environment.

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