



Development and Evaluation of System Restoration Strategies from a Blackout

Final Project Report

Power Systems Engineering Research Center

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Power Systems Engineering Research Center

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Executive Summary

System restoration following a blackout is one of the most important tasks for power system operators. However, few on-line computer tools are available to help operators complete that task in real-time. Indeed, most power system operators rely on off-line restoration plans developed for selected scenarios of contingencies, equipment outages, and available resources. Since the details of an actual blackout are hard to predict in the planning stage, a restoration plan can only serve as a guide in an actual system restoration situation.

In this research, we used novel approaches to transmission and distribution system restoration to design modules that can be used in an on-line decision support tool. Using such a tool, once fully developed and tested, operators will be better able to adapt to changing system conditions that occur during an actual restoration. The research-grade modules include:

- *Generation Capability Optimization Module*
- *Transmission Path Search Module*
- *Constraint Checking Module*
- *Distribution System Restoration Module.*

With additional development work, these modules could be linked and coordinated by a Strategy Module. Testing demonstrated the viability of these modules in identifying restoration decisions that we believe will reduce restoration time while maintaining system integrity. Ultimately, this will lead to lower outage costs for blackout events.

The four developed modules provide an automated and “best adaptive strategy” procedure for power system restoration. Future work will be needed for extensive testing, implementation planning, and actual implementation in a real-time operational environment.

Part I. Optimal Generator Start-up Strategies for Power System Restoration (work done at Iowa State University)

During system restoration, generation availability is fundamental for all stages of system restoration: stabilizing the system, establishing the transmission path, and picking up load. The generator start-up strategy is intended to provide an initial starting sequence of all black start or non-black start units. Available black start units must provide cranking power to non-black start units in such a way that the overall available generation capability is maximized. The corresponding generation optimization problem is combinatorial with complex practical constraints that vary with time. Two methods were developed and demonstrated for a *Generation Capability Optimization Module*.

First, by taking advantage of the quasiconcave property of generation ramping curves, a two-step algorithm was used for the generator start-up sequencing problem. The optimization problem was formulated as a Mixed Integer Quadratically Constrained Program (MIQCP). The solution method breaks the restoration horizon into intervals and develops the restoration plan by finding the status of each generator during each time

interval. Optimality is achieved for each step individually. The algorithm was tested using PECO data.

Second, we derived a new formulation of the generator start-up sequencing problem as a Mixed Integer Linear Programming (MILP). The linear formulation leads to a global optimal solution that outperforms other heuristic or enumerative techniques in both quality of solution and computational speed. The IEEE 39-Bus system was used for validation of the generation capability optimization. The simulation results demonstrated the high efficiency of the MILP-based generator start-up sequencing algorithm.

Part II. Transmission System Restoration with Constraints Checking (work done at Arizona State University)

A *Constraint Checking Module* is needed for a restoration computer tool. After a system blackout, parallel restoration of subsections of the system is an efficient way to speed up restoration. The system sectionalizing strategy determines the proper splitting point to sectionalize the entire blackout area into several subsystems. Parallel restoration can be carried out in each subsystem. For a large scale power system, this system sectionalizing problem is complicated due to black start and generation/load balance constraints. For system sectionalizing, we used an ordered binary decision diagram method that quickly finds the splitting points. Simulation results on the IEEE 39-Bus system showed that the method successfully sectionalized the system in a way that satisfied the two constraints. The method was implemented in the *Constraint Checking Module*.

A *Transmission Path Search Module* enabled optimization of the restoration sequence for linking the subsystems into a larger system, thereby gradually reducing the number of subsystems to zero. An objective transmission restoration path selection procedure, with the option to check constraints, may be better able to handle unexpected system changes during restoration and still provide the information needed by system operators for completing the restoration process. We developed a path selection approach that used power transfer distribution factors (PTDFs) for large-scale power systems. Two types of restoration performance indices were computed. They included all possible restoration paths. The computed indices were ranked, then PTDFs and weighting factors were used to determine the ordered list of restoration paths. This method enabled load to be picked up by lightly-loaded lines or by relieving stress on heavily-loaded lines. Successful test results of the *Transmission Path Search* and *Constraint Checking Modules* were obtained by using the IEEE 39-Bus system and by doing a realistic restoration exercise for the western region of Entergy's transmission system.

Part III. Automated Restoration of Power Distribution Systems (work done at Arizona State University and University of Tennessee)

During a system-wide restoration process, distribution system restoration is a critical task to help reduce economic losses and public dissatisfaction brought by a service interruption, especially in restructured competitive electricity markets. In this project we showed that fast, practical computational tools can be used to provide guidance for a distribution system restoration process that adapts to real-time system conditions. The tool can support decisions by operators during the restoration process by providing

customized plans for specific system conditions. This form of automated (or, alternatively, semi-automated) 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.

The computer tool for the operator permissive distribution system automation approach used optimization algorithms, in particular, the Lagrangian relaxation method and Binary Integer Programming. Using the tool, restoration plans are developed using the objective of minimizing outage cost and restoration time for a specified percentage of system load restoration. Other objectives that consider a weighted priority ranking or system security may also be adopted by replacing the cost function with the pertinent objective function. Due to the dual characteristics of the Lagrangian relaxation method, global convergence is not guaranteed as some constraints may be ignored during the optimization problem. In addition, the total accuracy of the solution will also depend on the estimates used for load and expected available generation. Matlab codes for the ***Distribution System Restoration Module*** are given in the report.

The developed algorithms were tested on 4-feeder and 100-feeder test systems under several blackout scenarios. The results showed that automated restoration is practical for small and modest size systems (e.g., to at least 100 feeders and 25 substations). The tool is expected to reduce restoration times significantly. The number of hours per year required for restoration depends on the specific nature of the given distribution system. However, a system with system average interruption duration of three hours per year, for example, could be reduced to two hours per year. Networked distribution systems have the potential for dramatic reduction in system average interruption duration per year (e.g., by an order of magnitude).

Future work related to the distribution system restoration problem will enhance the models used in the tool to fully represent a practical restoration plan for a distribution system. Some needs for future development include:

- Further modeling of the cold load pick up phenomena
- Evaluation of the impact of phase sequence in capacitor switching
- Evaluation of the effect of system transmission and system voltage profile constraints in the distribution system restoration problem
- Determination of the role and candidacy of this tool as part of smart grid initiatives
- Development of demonstration projects for automated restoration
- Additional system configurations and various system constraints.

Part IV. Automated Optimal Transmission System Restoration (work done at Washington State University and University of Tennessee)

Transmission system restoration is critical to the integrated power system restoration process. It builds the transmission line skeleton to facilitate the restoration of generation and the distribution system. Generation units rely on this skeleton to pick up appropriate amount of loads to maintain a viable balance during restoration. Distribution substations rely on this skeleton to restore lost loads. The corresponding optimization problem is of combinatorial nature. The restoration algorithms assist system operators during restoration by determining the order and time at which transmission lines should be energized.

The optimal transmission path search is formulated into a Mixed Integer Quadratically Constrained Programming (MIQCP) problem under the assumption that the transmission network is lossless. Since the quadratic terms in the MIQCP problem are all pseudo (i.e., they are multiplication between a binary variable and a real number), a general rule is derived and proved to linearize these pseudo-quadratic terms. With the linearization of these pseudo-quadratic constraints, the MIQCP problem is converted to a Mixed Integer Linear Programming (MILP) problem. With the assistance of other more detailed analysis programs, the feasibility of a transmission line restoration plan can be checked. Any necessary adjustments can then be performed to satisfy all system constraints, static or dynamic.

The main contributions of this research are:

- Novel approaches for determining proper transmission system restoration strategies.
- Formulation of the optimal transmission path search as an MILP problem.
- Formulation and proof of a standard rule to linearize a pseudo-quadratic term.

This work constitutes an extension to transmission system restoration that was described in Part II. The viability of this approach was demonstrated on a 6-bus system.