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CIGRE US National Committee
2022 Grid of the Future Symposium

Real-Time Electromagnetic Transient Simulation of the Synchronization of Two Core Islands During Blackstart Procedures

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SUMMARY

System restoration planning has traditionally been supported by steady-state and dynamic analysis. Today, more robust simulation models are required to incorporate high-bandwidth inverter-based resources, FACTS devices, and other components with fast time constants into the existing grid. As such, real-time electromagnetic transient (EMT) simulation has become an attractive option for future transmission planning and training operations. Of particular interest to Dominion Energy Virginia is the use of RTDS Technologies' Real-Time Digital Simulator (RTDS) architecture for studying the behavior of a system during restoration from a wide-spread loss of service, also referred to as blackstart procedures. While previous studies have investigated the use of the RTDS for specific aspects of system restoration planning, the use of large-scale system models for blackstart planning and training has been mostly unexplored. This work presents preliminary efforts to model Dominion's full transmission system in RTDS to perform real-time EMT simulations of the system restoration process. Dominion's system restoration plan is briefly discussed to outline constraints for the development and operation of the system model. A test case then simulates the formation and synchronization of two stable, isolated subsystems of the grid, referred to as core islands, formed by at least one self-starting blackstart unit sequentially energizing the lines and loads surrounding it. The results of the test case show the functionality and fidelity of real-time EMT simulation for blackstart planning and system operator training. Further improvements to the model and applications for its use are proposed. Results suggest it has potential as a scalable planning and training tool for not only standard blackstart operations, but also for the integration of inverter-based resources into these operations.

KEYWORDS

Blackstart, system restoration, real-time simulation, electromagnetic transient simulation, core-island restoration, core-island synchronization, RTDS

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I. INTRODUCTION

While the electrical grid is designed to withstand equipment failure and other hazards, not all contingencies can be anticipated. With the increasing likelihood of natural disasters due to climate change and the growing risk of cyber-attacks, the ability of a bulk electrical system to recover quickly from a partial or total system failure is more important than ever. The process of recovering from a wide-spread loss of electrical power supply, referred to as a blackstart, requires system operators to effectively assess the situation and restore stable service to as large of a region as possible as quickly as possible. The decisions made to accomplish this are traditionally supported by the results of steady-state and dynamic simulation both in contingency planning and in real time once the restored system is strong enough to support it. However, as the electrical grid evolves to support the complex interactions between high bandwidth inverter-based resources and conventional turbine-generators, more robust simulation methods must be established to determine optimal blackstart procedures.

By representing systems as a set of differential equations solved through trapezoidal integration, electromagnetic transient (EMT) simulations can provide a more accurate representation of these systems. They can also model phenomena, such as transformer saturation and power electronic device switching, that cannot be achieved with transient stability programs alone [1]. Real-time EMT simulation presents several benefits over offline EMT simulation, including incorporating physical control and protection equipment through hardware-in-the-loop testing and obtaining feedback in real-time. Historically for utilities, real-time simulation has been reserved for small-to-medium-scale systems. However, as computational processing has become more powerful and less costly, utilizing real-time EMT simulation for planning and system operator training has become a realistic option for high-fidelity dynamic modelling.

Real-time EMT simulation is generally performed on highly parallel, multi-core, multi-processor systems with simulation time-steps in the tenths of microseconds, such as the Real-Time Digital Simulator (RTDS) from RTDS Technologies. In recent years, this real-time simulation architecture has been used to investigate aspects of blackstart operations such as the function of differential protection relays under weak grid conditions [2] – [4] and the simulation of a remedial action scheme as well as the system's response to its execution [5]. Large-scale modelling with RTDS has been shown to be feasible using external precision clock sources and Bergeron transmission-line models as an interface between simulation subsystems [6]. This functionality has been explored recently to model renewable energy bases in China [7] as well as in a closed-loop testbed for a proposed voltage source converter-base, high-voltage DC interconnection in Tasmania [8].

Despite these numerous studies, the large-scale modelling of an entire transmission system specifically for the purposes of blackstart planning has been mostly unexplored. Developing a geographically and topologically accurate model of the Dominion Energy's transmission system in RTDS would allow system operators to simulate the entire system restoration process while receiving accurate and detailed feedback on the system's response to their planned actions in real time. Such a model would provide a valuable decision-making and training tool to system operators.

This paper describes a section of Dominion's transmission system that was modelled using RSCAD; it consists of four cranking paths from blackstart units to nuclear substations and the paths connecting them. This model was simulated on two RTDS racks in real-time to demonstrate the process of re-establishing and synchronizing two isolated core islands in the event of a total system blackout. Each island is formed by at least one blackstart unit sequentially energizing the lines and loads surrounding it to form a small, stable subsystem of the grid. In Section II of the paper, Dominion's System Restoration Plan and blackstart procedures are discussed to establish guidelines for the development of the model. In

Section III, the model's development is outlined and a preliminary test case verifies the system model's functionality and fidelity. Finally, in Section IV, possible future uses for the model are discussed.

II. DOMINION ENERGY'S SYSTEM RESTORATION PLAN

Dominion Energy's System Restoration Plan (SRP) provides detailed guidelines for restoring its bulk electrical transmission system facilities following a major disturbance or blackout event. The plan is in compliance with NERC EOP-005-2 for System Restoration from Blackstart Resources [9], NERC EOP-006-2 for Reliability Coordination [10], and PJM Manual 36 for System Restoration [11].

Following a system-wide blackout, Dominion utilizes a bottom-up, core-island restoration approach to enable a shorter overall recovery time and a greater availability of fault current in the system to clear faults faster [12]. In contrast to a top-down approach, where the system is restored from the neighboring interconnection, a bottom-up approach begins by bringing designated self-starting blackstart generation units online without relying on external resources. From these units, cranking paths can be energized to deliver off-site power first to nuclear stations to ensure safe shut-down. An example of a cranking path in DEV's system is shown in Fig. 1 below.

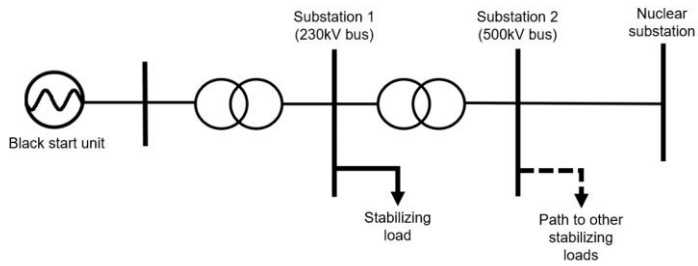

Fig. 1: Example of a cranking path in Dominion's system from a blackstart generation unit to a nuclear substation

After all critical and high-priority loads have been supplied with power, other lines, loads, and machines with a hot start time of less than four hours can then be sequentially energized to form a stable core island. Multiple core islands will be developed simultaneously and ultimately synchronized to return the system to normal operating state. During this process, several operational considerations must be observed. The system frequency must remain between 59.5 and 60.5 Hz to prevent under-frequency or over-frequency relays from tripping. Voltages at generator terminals and across transmission lines must also be kept within ±5% of their nominal values, both to reduce the amount of capacitive reactive power introduced into the system and to help control the rise in voltage at the remote ends of lines as they are energized. Generators should remain within their minimum and maximum active and reactive power range to avoid damaging mechanical components.

When synchronizing two core islands, their voltage magnitudes and frequencies must be matched as closely as possible. The voltage phase angle between the two systems must be within an allowable tolerance level (as defined by system engineers for the specific area of synchronization) so that, when the breaker between them closes, the transfer of energy between the islands will be minimal [13]. The larger island should be more stable and maintain a constant frequency due to its larger load. It is recommended that the generation and loading of the smaller island be adjusted to match the frequency of the larger island. These synchronization guidelines are crucial. If the two islands are not closely matched in voltage magnitude, phase angle, and frequency, the resulting in-rush of current through the breaker could create flashovers, cause protective relays to erroneously trip, and damage mechanical components in machines.

The SRP also provides guidelines for counteracting capacitive reactive power introduced to the system by transmission lines. As a rule of thumb, the SRP specifies that 2 MW of load should be added for each MVAR to be absorbed when energizing lines. This will prevent generators from reaching their minimum excitation limits and tripping. Since extra-high voltage 500kV lines can easily exceed the reactive capabilities of individual generator units, they should only be energized once the network is stable and has a larger reactive capability.

III. TEST CASE

To observe the behavior of the system during the initial steps of the system restoration procedure in real time, a partial model of Dominion Energy's transmission system was developed in RSCAD. The model included four cranking paths -- two to each nuclear substation. This is because the SRP dictates that these would be the first energized paths to enable safe shutdown of nuclear generation facilities. Each nuclear substation and the substations along its corresponding cranking paths form the two hypothetical core islands in this test case. A path connecting the two islands was modelled to observe the behavior of the system when islands were synchronized along a standard transmission line. Breakers were included after each machine and load and at both ends of every transformer and transmission line to control the path being energized. The approximate configuration of the model is shown in Fig. 2 below.

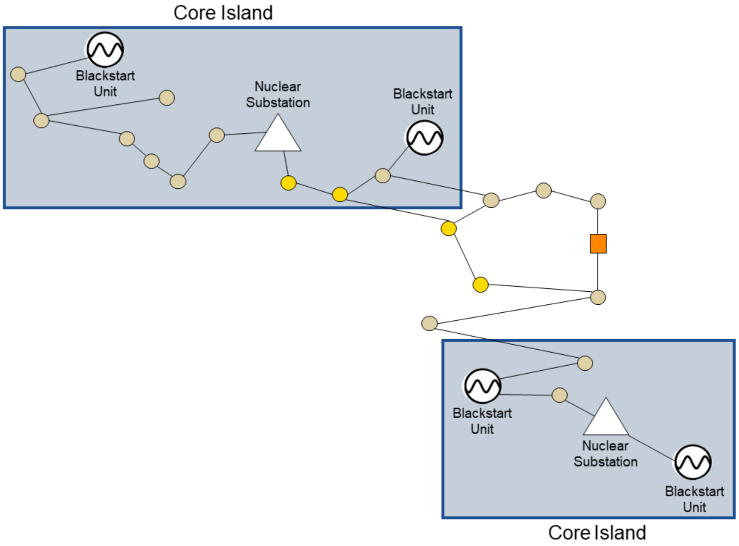

Fig. 2: Representation of a bottom-up, core-island restoration approach

The active and reactive power for the blackstart unit during the formation of the first core island, seen in Fig. 3, shows that both values were maintained within the rated limits of 190 MW of active power and -47 to 61 MVAR of reactive power. Similarly, the active and reactive power produced by the blackstart unit while it picked up a critical station service load at a nuclear substation during the formation of the second core island is shown in Fig. 4. Both values were maintained within the rated generator limits of 110 MW of active power and -27 to 77 MVAR of reactive power.

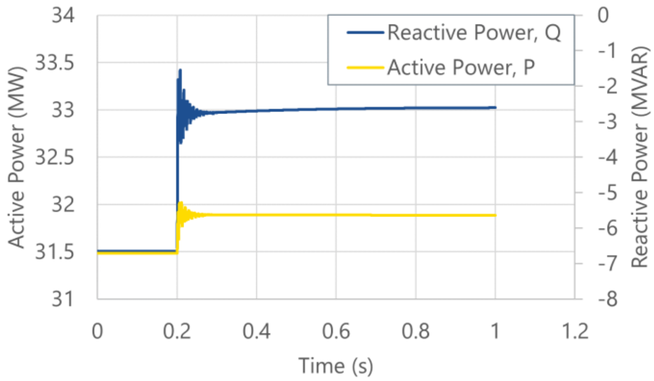

Fig. 3: Reactive and active power produced by a blackstart unit during the formation of the first core island

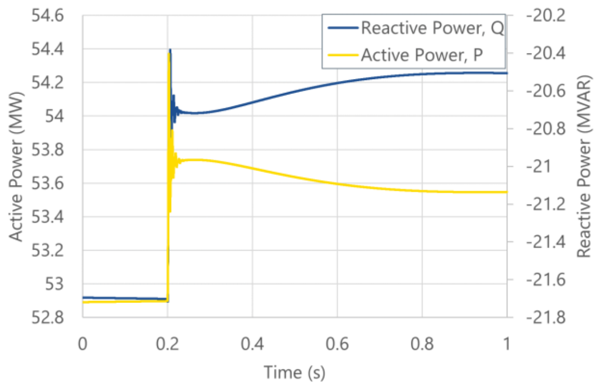

Fig. 4: Reactive and active power produced by a blackstart unit during the formation of a second core island

After the two core islands have been established, breakers along the path connecting the two islands are closed to energize portions of the line, until both sides of the path are energized up to a single breaker. For the purposes of this test case, the criteria used for synchronizing the two islands were a voltage magnitude difference less than 3%, a frequency difference less than 0.1 Hz, and a phase-angle difference less than 10 degrees. The breaker connecting the two islands was configured to close when all three conditions were met.

Fig. 5, Fig. 6, and Fig. 7 show the voltage magnitude, phase angle, and frequency measured on both sides of the synchronization point before and after closing the breaker. Figs. 5 and 7 show that the islands' phase voltage and frequency deviate immediately after closing the breaker but stabilize to a new steady-state value shortly afterward. Fig. 8 verifies that the magnitude of the in-rush current from closing the synchronizing breaker was not high enough to trip protective relays.

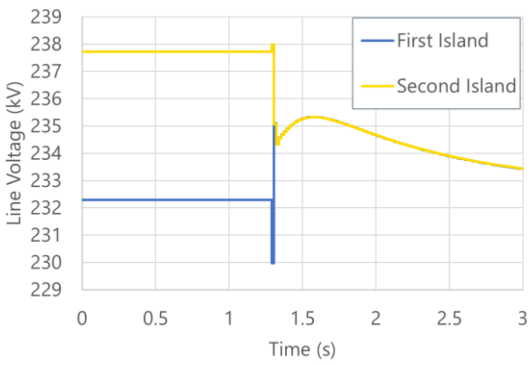

Fig. 5: *Phase voltage on both sides of the synchronizing breaker before and after closing*

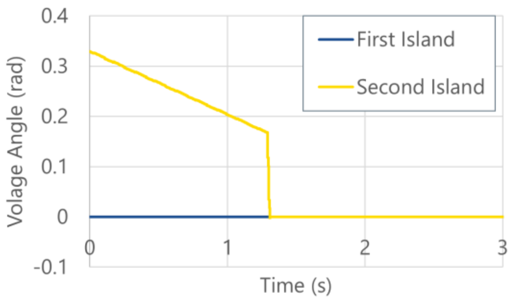

Fig. 6: *Voltage angle on both sides of the synchronizing breaker before and after closing*

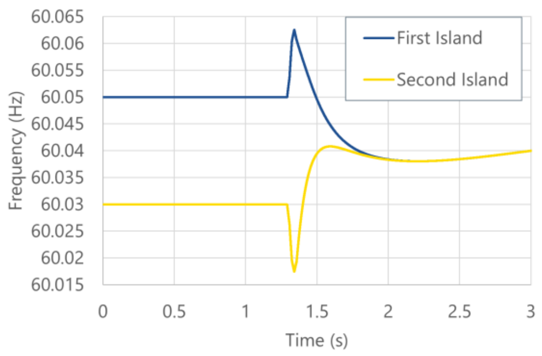

Fig. 7: *Frequency of the two islands before and after closing the synchronizing breaker*

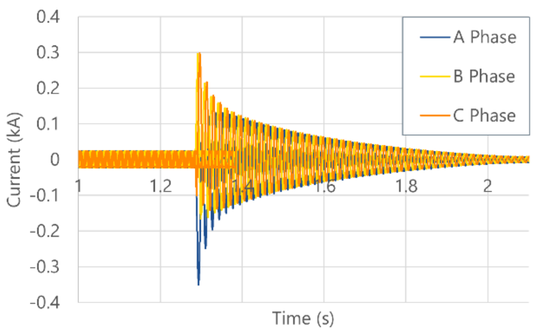

Fig. 8: Current through the synchronizing breaker before and after closing

IV. CONCLUSIONS AND FUTURE WORK

This work provides preliminary steps toward the development of a EMT simulation model of Dominion Energy Virginia's electric transmission system that can be run in real-time for planning and training purposes. A test case was designed to simulate the establishment of two core islands containing cranking paths to critical nuclear substation loads and also to synchronize the two areas by matching their voltage magnitude, phase angle, and frequency.

The continued development of this simulation has several potential uses. Since an EMT simulation has the ability to capture fast-transient dynamics, inverter-based resources, and FACTS devices can be modelled to investigate their effect on the transmission system and their potential use in blackstart procedures. The behavior of physical protection systems during restoration can be analyzed by integrating these devices with the simulation model through Hardware-in-the-Loop testing to ensure their functionality under weak grid conditions. Finally, once the full system is modelled, it can provide useful system restoration training for operators with near real-time feedback.

An added benefit of this study (while not in the scope of this paper) was the development of a pipeline to automatically import measured system data from an energy management system to initialize the model in RTDS. The pipeline automatically parses PSS/E .raw files containing complete transmission system data, measured every ten minutes by the energy management system, and generates an RSCAD RunTime script to initialize the RTDS model with up-to-date data. The development and validation of this pipeline will be the subject of a future study.

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