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Online Decision Support Framework for Power System Restoration by Use of Real-Time Simulation

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SUMMARY

Power system restoration following a wide-spread power outage is one of the most critical tasks for electric power grids. Since blackout impact increases with the duration of the outage, greater attention has been paid to developing decision support tools that can help operators and field crews restore service at a faster pace. The System Restoration Navigator (SRN) is a tool that can suggest an optimal system restoration plan following a complete or partial blackout while selecting specific milestones i.e., energizing a non-black start generator or a critical load. This paper further expands the SRN tool by introducing a real-time framework that can provide decision support during power system restoration. Several transient events were simulated in real-time in the IEEE 39-bus system to demonstrate the tool performance.

KEYWORDS
Blackstart, System Restoration, Real-time Simulation.

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Introduction

Power system restoration is the process of returning generators and transmission system elements to service and restoring load following an outage on the electric system [1]. Around the world, restoration is treated as a critical aspect of power system operations and planning. The timeline of a restoration process starts when a blackout (or a widespread outage) is recognized and ends when the power system reaches a normal operating state [2]. The focus during restoration is on re-establishing a sufficient skeleton of the network to achieve a stable operation so that resources and supply to end-use customers can be restored as expeditiously as possible while minimizing interruptions to societal life and the economy [3].

When implementing step-by-step facility energization procedures in real-time following a blackout, the power system behavior is quite different compared to its behavior during normal operation. The system being restored is weak, which can produce large and unacceptable deviations in voltage and frequency, thus causing potential regression. Therefore, the standard operating practices of normal power system may not be appropriate. Some of the technical issues that warrant special considerations are:

- Voltage performance: Energizing a transmission line can cause high open-end voltage, known as Ferranti voltage rise, due to line charging. Therefore, voltage control during restoration calls for multiple approaches such as careful energization of lines, use of shunt devices (reactors, SVCs, etc.), use of synchronous condensers, quick load pickup following line energization, removal of shunt caps, and so on.
- Frequency performance: During restoration conditions, frequency control requires a system operator's careful attention to load pickup because only a few generators may be online. An energization of even a relatively lightly loaded distribution feeder can have a significant impact on system frequency in the early stages of restoration. If the frequency deviation is too large, equipment damage or trip-out can result, which may lead to regression.

One of the challenges in developing a restoration plan is to sift through numerous possible restoration scenarios and paths, to identify those that are technically feasible. And, when implementing a restoration plan in an on-line environment following a blackout, the operators need to adapt to the actual outage scenarios and available resources. To address this, a novel analytical procedure in the form of a steady-state decision support tool i.e., System Restoration Navigator (SRN) was developed which power system operators and planners can leverage to develop, evaluate, and revise system restoration plans [4].

Real-time simulators (RTS), if available, can be used by operations personnel for rapid assessment of decisions during power system restoration especially in response to unfamiliar events and operating scenarios. It can be used to understand the full impact that an energization (switching operation) can have on system voltage and frequency performance. One of the main advantages of any Real-time Electromagnetic Transient (EMT) simulators over any off-line transient simulation program is for the applications involving inverter-based resources where interactions between primary power system components and protection systems become important.

In this paper, a conceptual framework is developed is to link SRN and RTS to provide real-time decision support during extreme events for a faster system recovery. The restoration plans suggested by SRN can be checked for transient performance in an RTS. In the future, the interface will be further developed for evaluating protection performance of the SRN provided restoration plans and to provide feedback to SRN to develop alternate restoration plans if previously suggested plans are not technically feasible and viable.

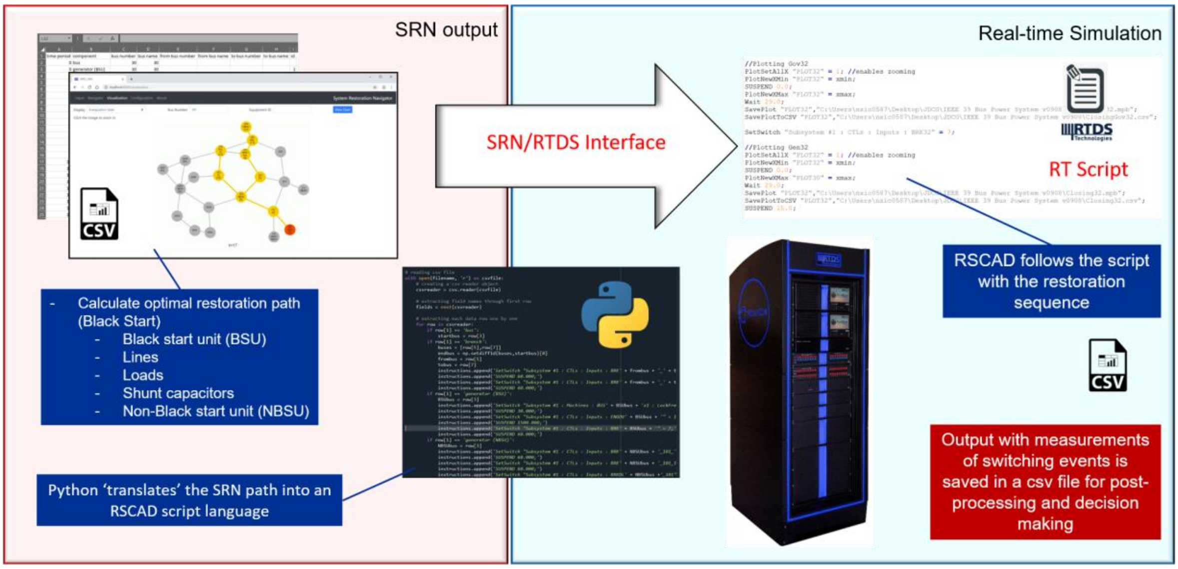

Fig. 1. Decision support framework for power system restoration by use of real-time simulation

Real-Time System Restoration Navigator

The SRN is a steady state-based tool that defines an optimal restoration path for a power system grid model. However, fast transients during generation and critical load energization will not be captured and it is important that restoration does not create conditions that may put grid components at risk (i.e. protection devices). The goal of this work is to validate the SRN restoration plan by performing a black start in an EMT environment with the added real-time element to have a more realistic result.

RT-SRN overview

The real-time system restoration navigator (RT-SRN) is a hybrid configuration that seeks to validate the restoration plan of a electric power grid in a RT-EMT environment by following the time-series switching actions provided by the SRN output. Fig. 1 provides an overview of the RT-SRN tool with an offline environment (SRN computations) and an online environment (RTS simulation) interacting between each other through a Python interface. In general, the flow of information during a black start is as follows: first, the SRN tool calculates the optimal restoration path from the black-start unit (BSU) up to the non-black start unit (NBSU), that is, the generator to be energized. The optimal path is saved in a csv file with the restoration commands (see Table I) and a visual mapping of the path is also provided as an output. Then, a Python interface translates the SRN restoration sequence to into an RTDS- interpretable script that provides breaker operations and timing inside the RTS. The output of the RT-SRN configuration is then saved in a csv file with monitored critical variables (i.e. voltage, current, generators speed, etc.) for further post- processing and analysis. With the described setup, the RT- SRN tool allows the following features for the restoration plan validation:

- Build existing cranking paths to key critical infrastructure in a benchmark power system implemented in a RTS environment
- Verify the cranking paths via extensive case studies in a RT-EMT environment considering system's transient and dynamic performance following each switching action
- Identify alternate cranking paths using the System Restoration Navigator (SRN), if any of the existing cranking path is unavailable or not viable from transient/dynamic considerations
- Simulate an extreme event in real-time and manually inform SRN on the simulated power outage

SRN

System Restoration Navigator (SRN) is a decision support tool for operators and planners to develop, evaluate and revise system restoration plans. It is meant to be used primarily by restoration planners to develop, validate and update restoration plans. Recently, underlying algorithms were extended to better assess restoration needs resulting from High-Impact-Low- Frequency (HILF) events such as Geomagnetic Disturbances (GMD), Electromagnetic Pulse (EMP), cyber/physical security attacks, etc. SRN mainly focuses on establishing cranking paths from blackstart resources to non-blackstart generators and picking-up critical loads. To achieve this objective, the following restoration actions include:

1. Energization of Blackstart units.
2. Cranking of Transmission paths.
3. Energization of non-blackstart units
4. Critical load pick-up

The key function of SRN is to determine an optimal cranking path to non blackstart units and critical loads considering the operational constraints of both generation side and transmission side.

Real-time simulation in RSCAD

SRN is a steady state-based tool that calculates the optimal restoration plan of a power electric grid. However, computation of the restoration plan will not capture fast transients (i.e., overvoltages and instabilities) during the restoration process. A large number of switching actions occur during restoration that may cause undesirable protection tripping or even put power grid components at risk. In real-time simulation, the objective is to obtain results at the transient level within the same length of time that a models' physical counterpart would. This emulates the real field behavior of the restoration process while being able to perceive any abnormal conditions. Moreover, having a RT-SRN tool opens the door to future hardware-in-the-loop configurations and analysis where actual protection devices may be tested.

For this work, RTDS, a real-time simulator tailored for electromagnetic transient (EMT) simulation of power system. This is possible with the RSCAD built-in library of detailed models as well as the RTDS simulator capability to run the simulations with small time-steps that can be as short as a few microseconds.

RT-SRN Optimal Restoration Plan: A Case Study with The IEEE 39-Bus System

Modified IEE 39-bus model

For validation of the RT-SRN configuration with the IEEE 39-bus system, a reduced equivalent of the New England test system [5] was used. The IEEE 39-bus system consists of 10 generation units and 46 transmission lines as shown in Fig. 2. This system model was selected given the flexibility it provides to test different restoration paths that can result from the combination of its 49 transmission lines.

1. Line breakers: To accommodate the IEEE 39-bus system for a black start process, several modifications in the system needed to follow the breakers operating sequence provided by the SRN tool were made. More than a hundred-line circuit breakers were added at both ends of

the transmission lines. Additionally, circuit breakers were added to loads given that some loads can be selected as milestones during the restoration and may be picked up during the process. Switching transformers is also possible as inrush current is very important to monitor during transformer energization after a blackout to monitor undesired tripping.

2. Governor and exciters: Given that the model needs to start energization from total blackout, TGOV1 governor and IEEE Type 1 exciter to every unit was added. During black start, the governor and exciter are responsible to ensure nominal frequency and rated voltage levels.
3. Non-black start unit Auxiliary Loads: Auxiliary loads were added to emulate lighting, pumps and valves needed for the NBSU start-up. Typical topology ranges around 5% of the generator rating with 3% static load and 2% dynamic load. The dynamic load was modelled as an induction motor. Fig. 3 shows the IEEE 39-bus system section downstream of bus 10 of the auxiliary load. The static and dynamic loads are connected to bus 101.

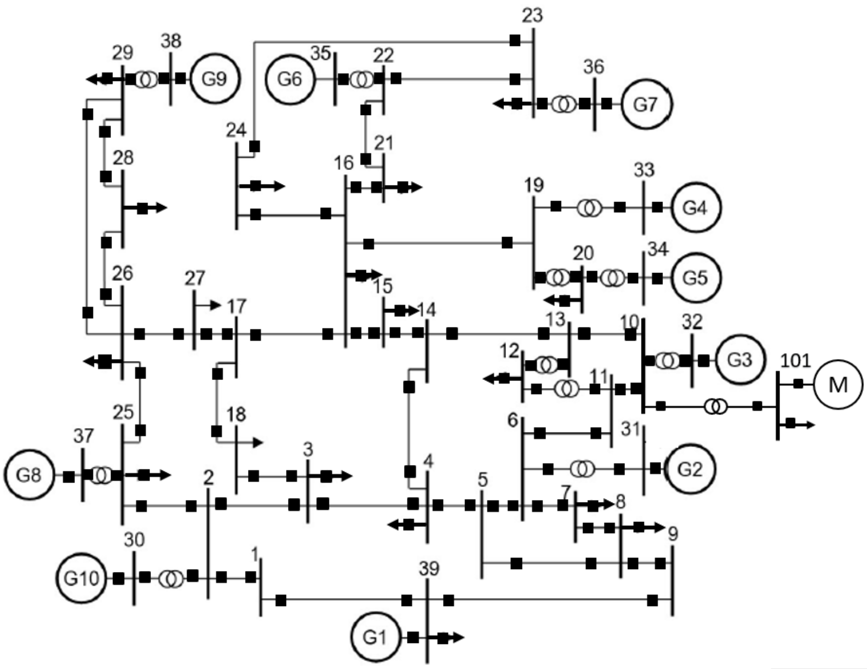

Fig. 2. Single-line diagram of modified IEEE 39-bus system

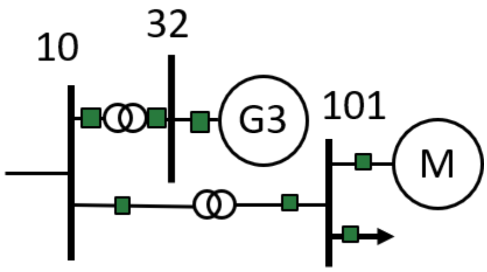

Fig. 3. Added auxiliary loads for NBSU

Optimal Restoration Path

Fig. 4 shows the optimal restoration path output calculated with SRN. The topology of the IEEE 39-bus system is depicted on the left side of this figure with every circle representing the buses from the IEEE 39-bus system. For this case study, a restoration plan was needed to restore power to the NBSU (generator 3 at bus 32). The BSU is depicted by the orange circle while the yellow circles and lines represent the energized nodes and branches along the optimal path identified by SRN. Table I shows the step-by-step restoration sequence.

TABLE I RESTORATION PLAN FOR IEEE 39-BUS SYSTEM

Step	Component	Bus number	From bus number	To bus number
1	generator (BSU)	30		
2	line		30	2
3	line		2	3
4	load (NCL)	3		
5	line		3	4
6	line		4	14
7	line		14	13
8	line		13	10
9	line		10	101
10	load (CL)	101		
11	line		10	32
12	generator (NBSU)	32		

The image on the right of Fig. 4 shows the IEEE 39-bus system modelled in RSCAD. The circuit breakers that will follow the operation sequence during restoration have been highlighted in yellow (following the same sequence in Table I).

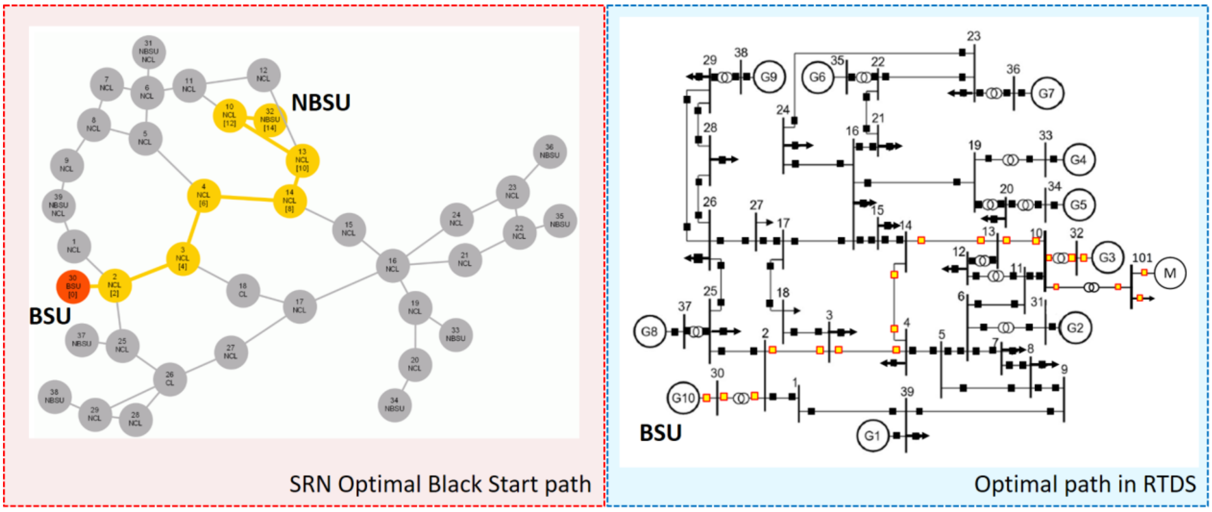

Fig. 4. Restoration path output from SRN (left) and model in RTDS (right)

Fig. 5 shows the speed and voltage during the startup of the BSU located at bus 30 (step number 1 from Table I). BSU readiness time takes approximately 20 minutes, a behavior that depends on the dynamics of the controller specifics, to stabilize to the nominal speed. Fig. 5 also shows that voltage reaches the steady state in twenty seconds.

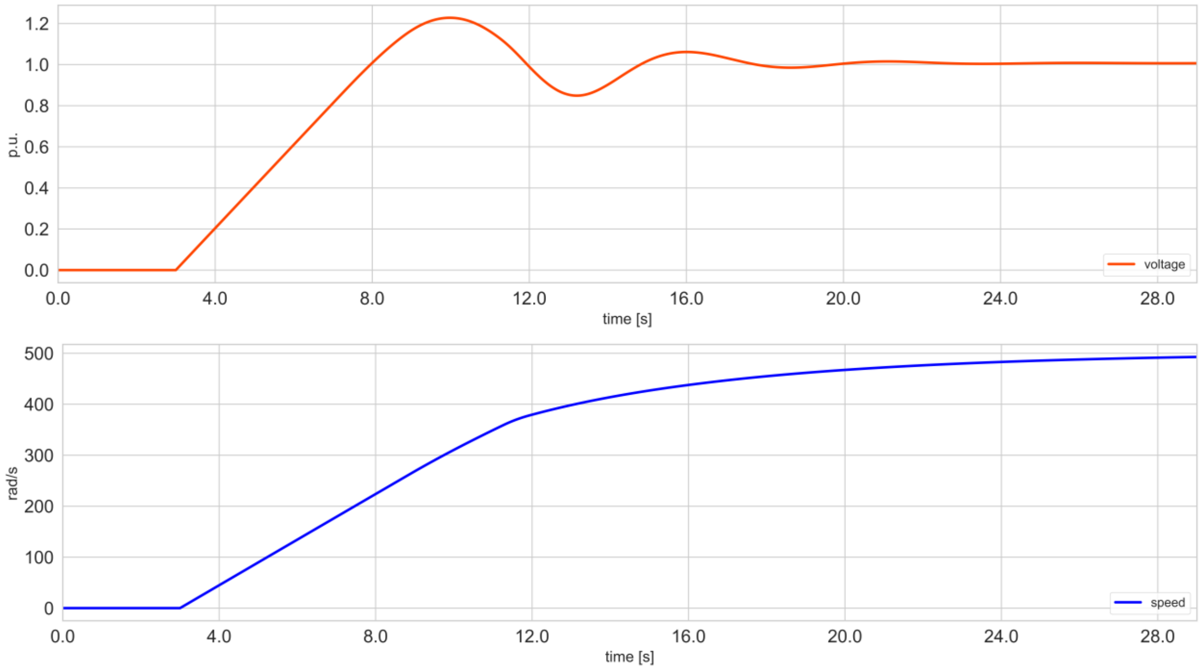

Fig. 5. Voltage (top) and speed (bottom) measurements from black start unit (BSU) startup

In the IEEE 39-bus system, a transformer located at line 2-3 steps-up the voltage from 13.8kV to the grid voltage of 345kV. Fig. 6 shows the transformer inrush current when the transformer serving station service loads of the non-black start generator at Bus 10 (step 2 from Table I). The interest in monitoring transformer inrush currents is to make sure that energizing the transformer from a weaker system during blackstart does not cause any undesired relay operation. The inrush from a weak source could be even worse if the transformer had any residual flux. The inrush current could greatly exceed the nominal current. If the transformer core still contains residual magnetism, the first peak current can even reach the level of the short-circuit current. These high currents can cause undesirable effects, such as mechanical deformation of the windings, incorrect triggering of protection equipment, increased stress for the installation, and voltage dips in the system.

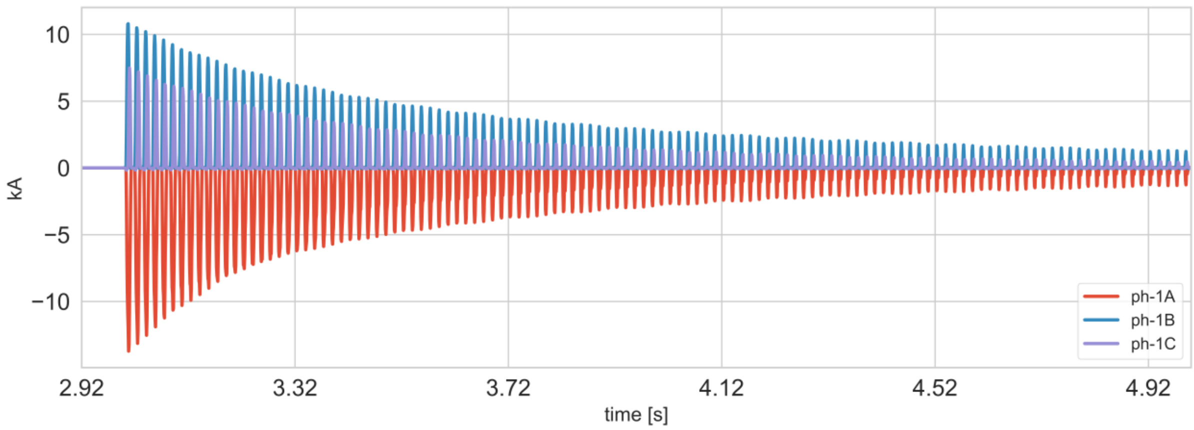

Fig. 6. Transformer inrush current measurements at line 2-30

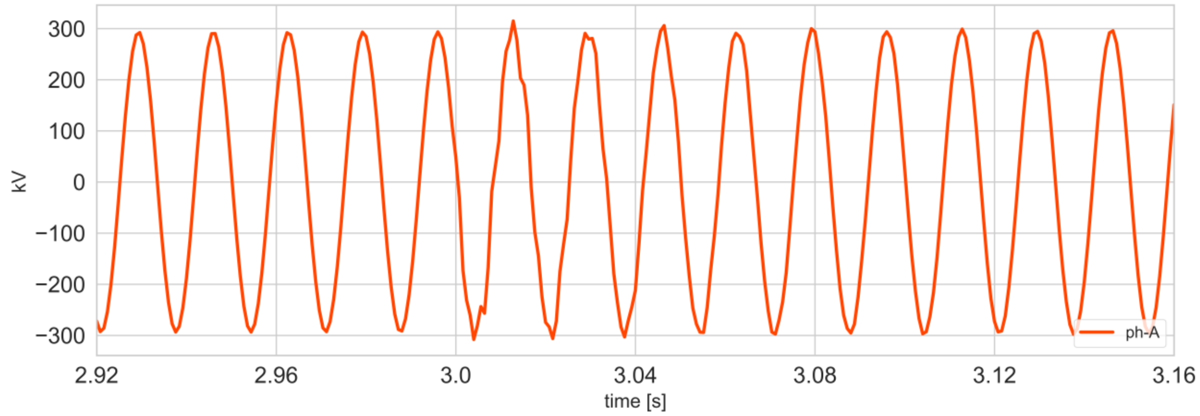

Fig. 7. Voltage measurements from bus 2 when closing circuit breaker at the beginning of line 2-3

After energizing line 2-30, step 3 follows in the restoration path, energizing line 2-3 (see Table I). Fig. 7 shows the voltage when breaker at the beginning of line 2-3 closes, as seen from bus 2. The interest in monitoring Bus # 2 voltage is to see line energization switching voltage transient resulting from energizing the line capacitance. In a normal black start, line 2- 3 can be assumed to be unenergized for considerably long time and may not have any trapped charge. When the breaker closes at the beginning of line 2-3, the travelling wave finds the open circuit breaker at the far end, bouncing back and elevating the voltage to what could be dangerous levels. This overvoltage can be observed in Fig. 8 which shows the measurements from the far-end breaker at line 2-3. In this figure, voltage at bus #2 (red) and at the end (blue) of line 2-3 are superposed for visualization purpose. It can be observed that the voltage at the end of the line reaches a higher voltage level (over 400 kV) than at the beginning of the line. Similar behavior for line energization was observed for steps 4 through 9.

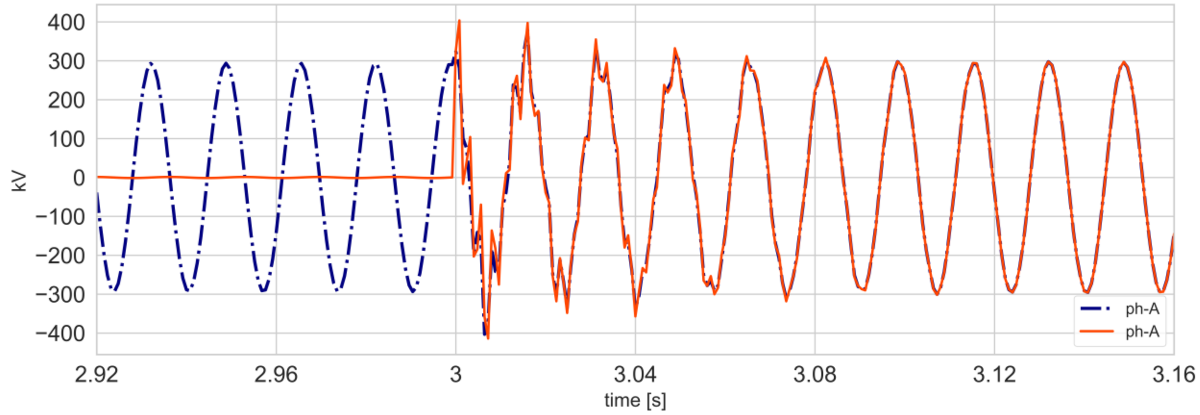

Fig. 8. Voltage measurements at bus #2 (red) and far-end (blue) of line 2-3 when the line becomes energized

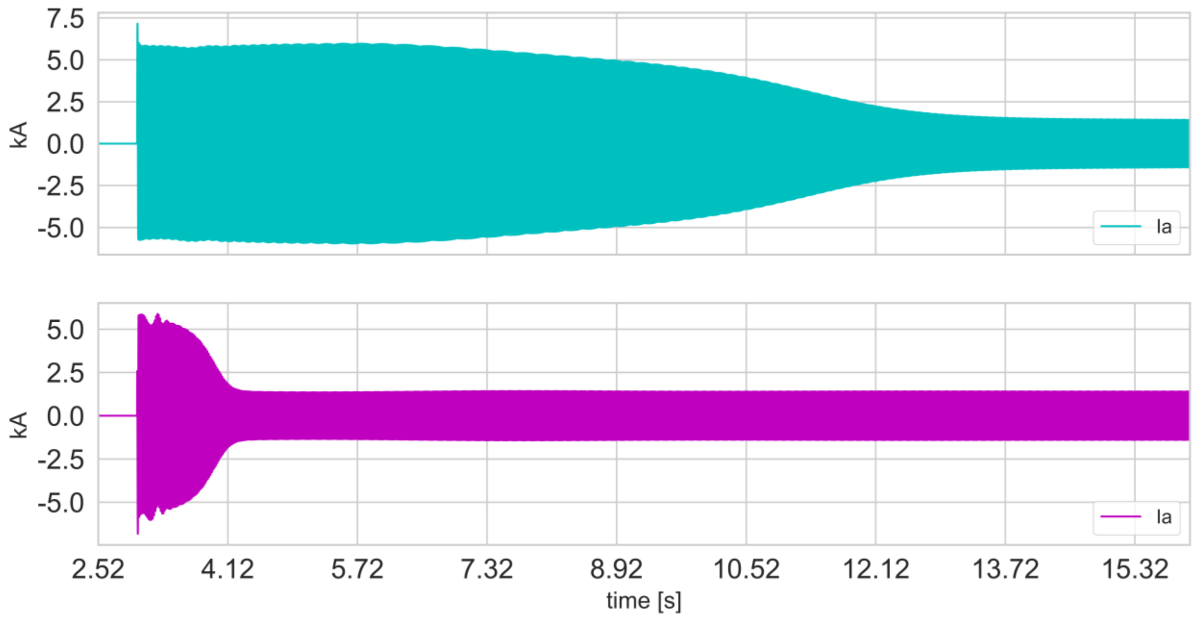

Fig. 9. Current measurements from auxiliary motor dynamics with high (top) and low (bottom) inertia

Another point of interest is detecting any abnormal conditions or events while picking up auxiliary loads during black start. Picking up the auxiliary loads that help starting the NBSU (pumps, valves, lighting, etc.) is defined as step 10 in Table I. As a steady state-based tool, SRN will not capture any transients. The RT-SRN tool can be utilized to observe the behavior of the NBSU auxiliary dynamic load, i.e., the induction motor. It is important to detect abnormal conditions that may cause undesirable tripping such as high starting current of the motor. As an example, a comparison between starting currents and the dynamic performance of the induction motor at node 101 with different inertia parameters is shown in Fig. 9. As expected, starting the motor requires a higher starting current for less than a second for the case with low inertia (top Fig. 9). It can be observed that for the high inertia scenario (bottom Fig. 9), a higher starting current is needed for a longer period of time until the induction motor reaches the rated speed. The speed for low and high inertia parameter comparison is shown in Fig. 10. Again, the high inertia motor takes longer to reach the nominal speed during the motor starting. As stated previously, it is important that starting current remains below the threshold of protection relays to avoid unexpected tripping.

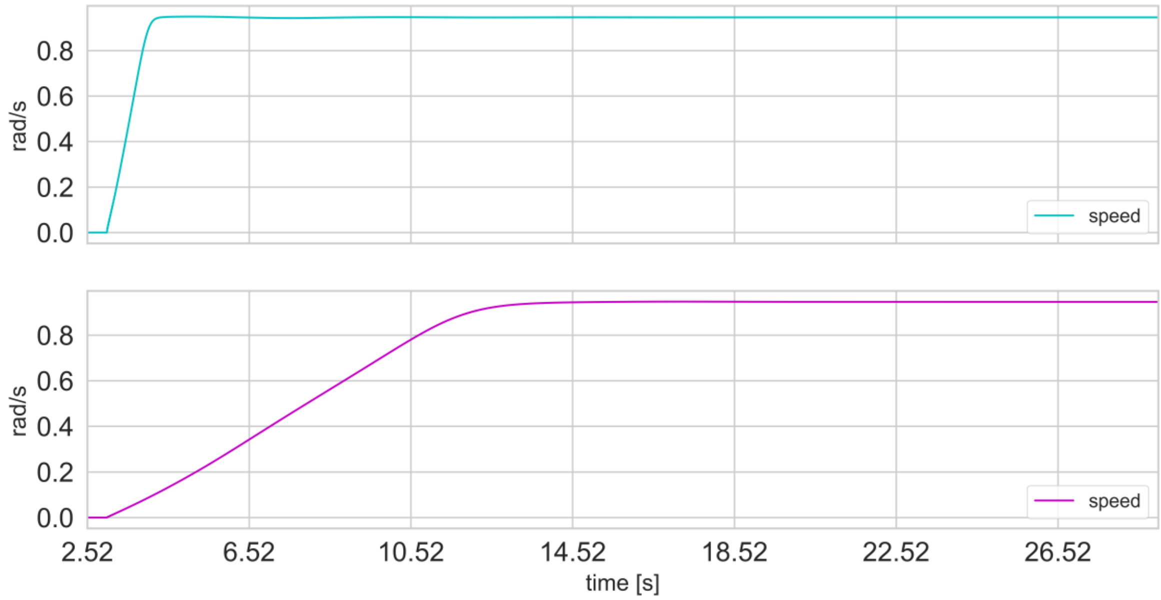

Fig. 10. Speed measurements from auxiliary motor dynamics with low (top) and high (bottom) inertia

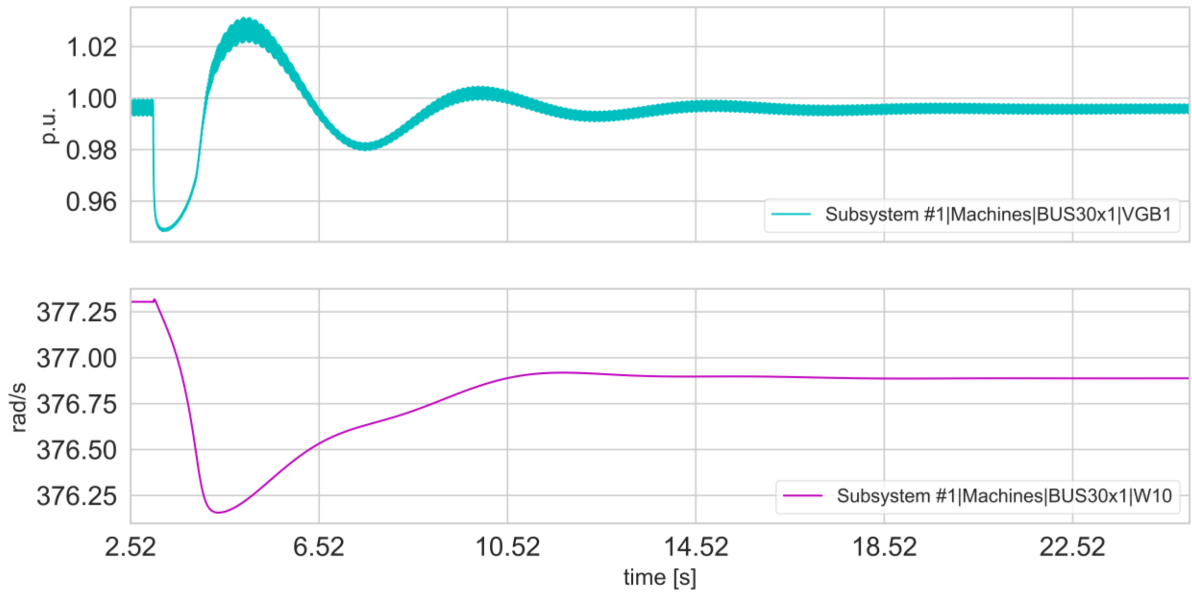

Fig. 11. BSU response to low inertia auxiliary load startup

Fig. 11 shows the BSU dynamics during the induction motor (auxiliary load) startup. It can be observed that voltage at the BSU deviates from its nominal value significantly for around 7 seconds. Similarly, the speed of the generator varies according to the motor dynamics during its startup. In the high inertia case (Fig. 12), the generator takes longer to stabilize its rated voltage, while reaching a lower speed than in the low inertia scenario that slowly recovers to full speed. It is important that protection and operation engineers are aware of these conditions during black start.

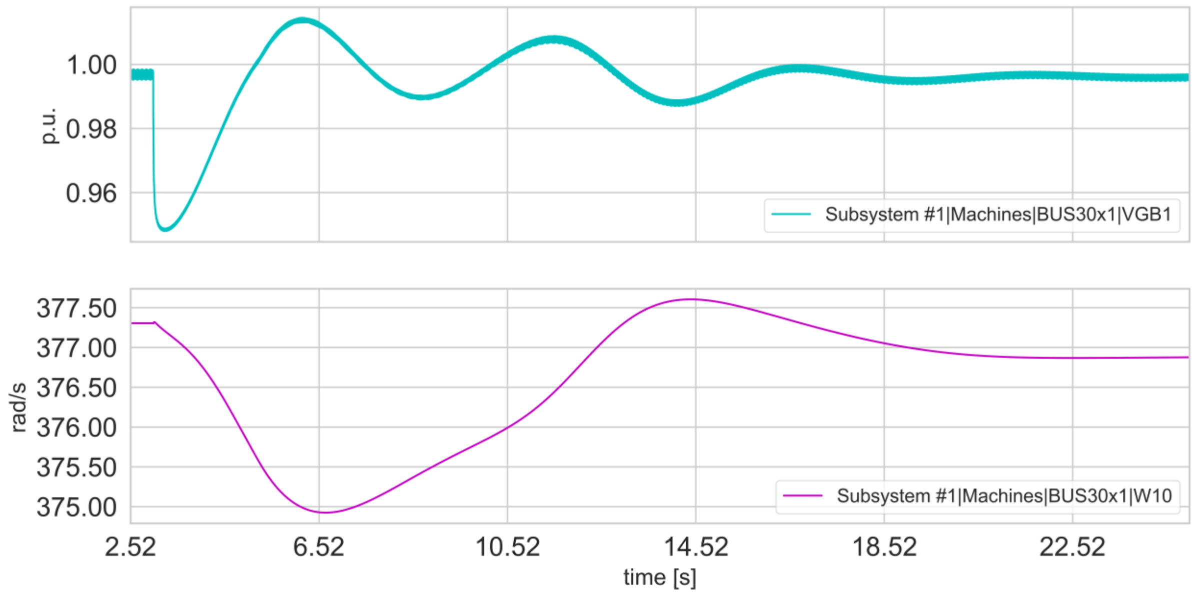

Fig. 12. BSU response to high inertia auxiliary load startup

Conclusions

This paper presented the conceptual framework that facilitates computation of a restoration plan during total blackouts while providing awareness of possible contingencies that may occur during switching operations. As such, picking up critical loads, transmission line energization, and transformer inrush current are some of the points of interest during a restoration plan that have been simulated and analysed in this paper. Using an EMT simulation tool in conjunction with OPF-based SRN tool has enabled the emulation of the real field behaviour of the restoration process while being able to perceive any abnormal conditions even at the transient level. Moreover, having a real-time EMT simulation tool opens the door to future hardware-in-the-loop configurations and analysis where actual protection devices may be tested to assess their performance during system restoration.

Future work includes development of an interface between RTDS and SRN that provides power outage information upon extreme events to facilitate real-time decision support during system restoration.

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