Simulations for Validation of a Black Start Restoration Plan using PSCAD

Jingxuan (Joanne) Hu, Bruno Bisewski

***Abstract*--This paper summarizes simulation studies for a black start restoration plan. The studies were carried out using the PSCAD/EMTDC, a three-phase time-domain power system simulation program, which provides a platform for simulation of the events in a restoration sequence which are as close as possible to the actual system. The program can simulate aspects of system performance such as saturation and inrush that could be difficult or impossible to simulate using other power system study tools such as PSS/E and PSLF. The simulations included step-by-step energization of equipment and loads in two separate electrical islands which are designated as Island 1 and Island 2 followed by interconnection of the two Islands. The study indicated that the proposed black start restoration sequence was reasonable and workable but it would be necessary for the operator to confirm that there were adequate reactive margins prior to each major transformer energization event. As a rule of thumb, it was established that, for relatively small systems, if the total connected load did not exceed about 60% of the rating of the generators then sufficient reactive margin would be available for the next energization event.**

***Keywords*: Black Start Restoration, PSCAD/EMTDC, isolated system operation, cold load pickup, transformer energization, inrush, load representation, self-excitation, voltage sag**

I. Introduction

Black start restoration plans have been prepared by a transmission system owner to ensure that their transmission system can be restored as quickly and reliably as possible following a complete or partial blackout. This paper addresses the studies performed to evaluate and validate the restoration procedures as well as the black start machine capacity and limitation on the reactive power consumption to ensure a successful system restoration.

The black start restoration plan consists of the formation of two separate islands and the interconnection of these two islands which includes the energization of about thirteen transformers, fifteen 34.5kV and 46kV lines, loads pick-up at various locations and eight black start machines.

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II. Considerations for Operation during Black Start

Black out conditions can be associated with a localized or wide-area event. Specific problems concerning system behaviors during past experiences of black start and restoration have been discussed in [1][2][3][4][5][6]. System operators are faced with many challenges in restoring the system because the capacity of the system to perform its normal functions is significantly hampered by the limitations on generation and reactive power supply.

These limitations are a function of the number of generators that are connected and thus are variable and would change as the system is being built up from the first generator to the last connected component of the island that will be created. Thus, the operator needs to keep a running record of the available real and reactive margins as these quantities are critically important at all stages of the restoration process.

Operator(s) must also be aware that, during restoration, some functions that are generally provided on a system-wide basis such as frequency control and spinning reserve must be provided locally within each island.

Each of these differences is described briefly in the sections below.

A. Black Start Generation

Black start generator units are generators that have been designated to be used in the restoration of the system following a black-out. These units have independent sources of auxiliary power to be used for start-up, protection, cooling and other functions that may be needed to start and run the generator.

To ensure stability, it is necessary to load the generator to its minimum load to ensure stability prior to proceeding with energization of other system components. Generally the load would be local load connected at the local distribution voltage level as applicable. The minimum loading of a generator is unit dependent and is typically 30 to 60% of the generator full-load rating.

B. Governor Droop

Generators are equipped with governors to maintain their speed as the load changes. This is accomplished by adjusting the inputs to the prime mover to increase or decrease the power output in response to changes in the frequency of the system. Ideally all units in the system should have their governors set to the same value of droop. Then, for a given frequency drop, all units would share the load increase in proportion to their ratings.

C. Island Frequency Control using Isochronous Control

Unfortunately governor control with all generators on droop settings results in a steady state frequency error unless the output of at least one of the generators is increased or decreased to bring the frequency back to the nominal frequency of 60 Hz. [7]

This is overcome by selecting the governor control of one of the generators to isochronous control. When in this mode the output of this generator will be automatically adjusted to ensure that the frequency will be maintained at the nominal value possibly with a deadband as shown in Fig. 1. As this generator is adjusted, the frequency error will be reduced to approximately zero and all the generators operating on droop control will return to the preset operating. This means that the generator in isochronous control will effectively pick up all of the load changes that occur in the system and may become overloaded. To maintain load balance between generating units and to provide reserve margin in the isochronous unit it would be necessary to manually adjust the output of the generator units that are in droop control.

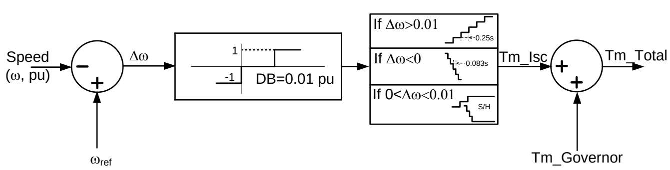

Fig. 1 – Implementation of Isochronous Controller used in the Studies

Only one generating unit in any isolated system may be selected to isochronous control. If there are two generators in isochronous control and the controllers are well-behaved, one may reduce its output to zero while the other picks up the whole load. However, if the two isochronous controllers are not well-behaved, there could be large sustained power oscillations between the two machines.

D. Spinning Reserve

Spinning reserve is defined as the difference between the maximum output capability of the generators that are in service and the total load of the system.

In any system there must be more generating capacity than load to ensure that load changes due to consumer load pick-up or operator load pickup on distribution systems will not suddenly result in a shortage of generation capacity compared with the load. If this were to happen the frequency of the system would decrease until the generators tripped on under speed. Tripping of the first generator would likely result in total system collapse.

In small systems, such as those in a system restoration scenario, it is very important to maintain adequate levels of spinning reserve.

E. Load Pickup and Load Diversity

Load pickup will cause both a frequency and a voltage change in the system because load consists of both real and reactive components [8]. The composition of the load depends on area being served but will generally consist of a mixture of electric lighting and heating and will also contain a significant amount of small induction motor load associated with industrial processes, consumer appliances, air conditioning, fans and motors associated with farming activities

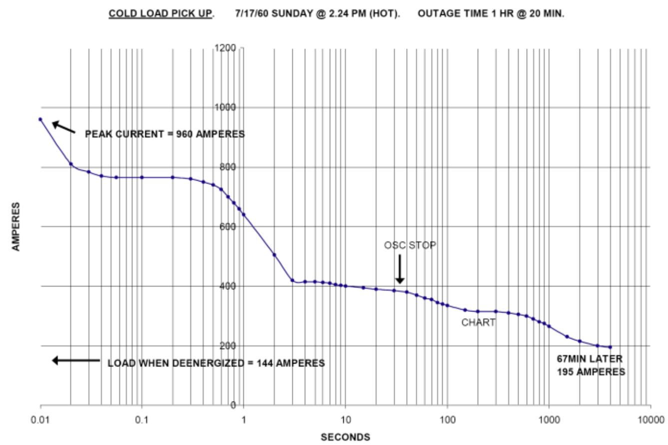

Fig. 2 - Example of Load Pickup after Outages for Summer Conditions [6]

It is well known by operators and distribution companies that the load that is picked up after an outage can be much larger than the load that was present when the circuit was de-energized. This is known as cold-load pickup. It is a consequence of consumers turning lights on during outages and the need to simultaneously restart of loads that are automatically controlled such as consumer refrigerators, freezers and heating or air conditioning. Cold load pick-up has been verified by measurement and typical results are described in [8] and shown for illustration in Fig. 2.

Given the diversity that is likely to be present it is necessary, when simulating the system, to model the load as realistically as possible. The load model should contain small induction motor load in addition to other load types such as constant current, constant real and reactive power and constant impedance.

F. Voltage Control and Reactive Margin

In addition to the limitations on real power, there are also limitations on capacity of the connected generators to supply or absorb reactive power.

Capacitor banks in the high voltage network which are used to help control voltage under normal conditions generally cannot be used in black start conditions for two reasons:

a) They are generally sized for normal short circuit levels. Under black start conditions the short circuit levels are significantly lower and thus switching the capacitor bank might cause excessive voltage change at the bus where it is switched.

b) The excessive capacitance may result in generator self-excitation. Generator self-excitation is condition that can occur under conditions where the generator is radially connected to a large capacitive load, generally a long unloaded transmission line or a large capacitor bank. Under self-excitation conditions, the high voltage bus could theoretically rise to the 2 to 4 p.u range neglecting transformer saturation, arresters and other factors such as corona on lines which would tend to limit the overvoltage. Even allowing for the action of arresters, this level of overvoltage would be sufficient to damage equipment.

G. Transformer Energization Inrush

Transformer inrush currents may occur during the energization of transformer [9][10].

The worst situation occurs when there is remanence (Φres) remaining in the core and the breaker closes in near voltage zero when the voltage is increasing in a direction which will add to the flux in the core. This causes very large asymmetrical currents to flow into to the transformer.

A major consequence of high inrush currents is that they result in consumption of a significant amount of reactive power. This causes a significant voltage drop at the terminals of the transformer. The voltage reduction during transformer energization is a function of the short circuit level of the system at that location and the rating of the transformer compared with the short circuit level.

The harmonics produced by transformer magnetizing inrush are not expected to cause any special issues as they would be sustained for only a few seconds and there will be no large capacitors connected in the system during the black start restoration. Thus there is no possibility of high harmonic voltages due to resonances.

III. Operational Criteria for Black Start

The following operational criteria were selected by the authors in the black start restoration studies to ensure that the system could be restored with minimal disturbance and acceptable power quality for customers.

a) Steady-state system voltages at every voltage level shall be regulated within ± 5% of nominal.

b) Steady-state system frequency should be regulated to within ± 0.3 Hz of nominal.

c) System shall be operated with adequate spinning reserve to ensure that an unexpected change in real power load due to consumer and or industrial load variation will not exceed that capacity of the connected generators to supply the load.

d) Sufficient reactive margin shall be maintained to ensure that an unexpected change in reactive load due to consumer and industrial load variation will not exceed the capacity of the generators to supply the demand.

e) All generators as part of restoration operation shall be equipped with governors. The steady state droop of all governors shall be set to the same value (nominally 5%) to ensure that, in the event of sudden load change, all machines will respond in the ratio of their ratings to automatically limit the frequency drop to the extent possible.

f) One generator in each island system shall be assigned the role of frequency control within each isolated network. This would be achieved by setting its governor to *isochronous control mode*, which simply means that the governor of that machine has an integral component as well as the normal proportional control or “droop” setting.

g) When synchronizing two island systems, the operator(s) shall ensure that the isochronous control in one system is switched off immediately prior to or immediately after synchronization occurs. Generally the larger generator should remain in isochronous control and the smaller generator should be switched to normal droop control. Prior to switching the generator to droop control the operator should make sure that its power setting is equal to the actual power of the machine.

IV. Study Methodology

Electromagnetic simulation program PSCAD/EMTDC was selected to simulate proposed black start restoration sequence as the program provides a platform which allows for simulation of the restoration plan as close as possible to the real system restoration. This type of program can simulate aspects of system performance such as transformer saturation and inrush currents that could be difficult or impossible to simulate using other power system study tools such as PSS/E and PSLF.

A PSCAD/EMTDC simulation model was developed with the capability to simulate the following

- Step by step energization of the system as defined in the black start restoration plan which includes the energization of two islands , Island 1 and Island 2, and interconnection of these two islands
- Voltage disturbances resulting from transformer magnetizing inrush
- Voltage and frequency disturbances due to load pickup and load dropping.
- Load modeling can include induction motors as well as other standard load models including constant current, constant PQ and constant impedance.
- Investigation of machine self-excitation
- Fundamental frequency and switching surge overvoltages due to line energization switching
- Generator synchronization
- Synchronization and Interconnection of already energized islands

V. Study Results

A. Step-by-step Simulation of the Black Start Restoration

A step-by-step simulation of the black start restoration was achieved by automated sequential switching control of all the devices. The time interval between switching events was reduced to the extent that was possible while still maintaining suitable separation between events so that each could be analyzed separately.

The simulation included a total of 57 switching operations. The two islands were started and run separately with switching proceeding in each Island until the two islands could be synchronized. The simulations also included load pickup which is not explicitly described in the operating procedure but which is required to provide the minimum loading for the generators.

An initial case was performed where system load was increased to 70% of generator capacity after bringing each unit on line. The results of this initial 70% load case indicate that Island 2 system would run out of reactive support and would collapse before the system can be synchronized. In the Island 1 there is slightly more reactive margin even though it is also loaded to 70% of generator capacity. The system does not collapse until the systems are connected at 195 seconds as shown in Fig. 3.

Based on this result, another case was carried out at a lower maximum load level at 60 % of generator rating. In the 60% load case which is shown in Fig. 4, the loads at several locations in Island 1were also configured to include 50% motor load to determine the impact of motor load dynamics during transformer energization. This represents the most conservative case for both steady state and dynamic reactive loading. The case is successful but there is less margin to exciter ceilings particularly in Island 2.

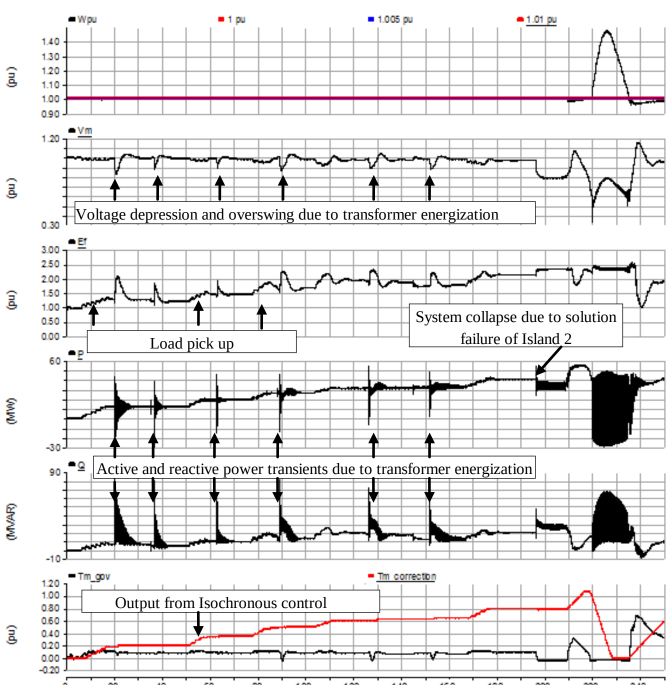

Fig. 3 Step-by-step Energization of the Island 1 with black start Generators loaded to 70 % of rated Capacity with modeling of Transformer Remanence

The 60% load case was also rerun with the assumption that there is no remanence in the transformers. This represents a very favorable case as there is significantly less reactive power demand on transformer energization due to lower inrush currents. The overall performance is significantly better as there is more reactive margin as can be seen by comparing margin to exciter ceilings.

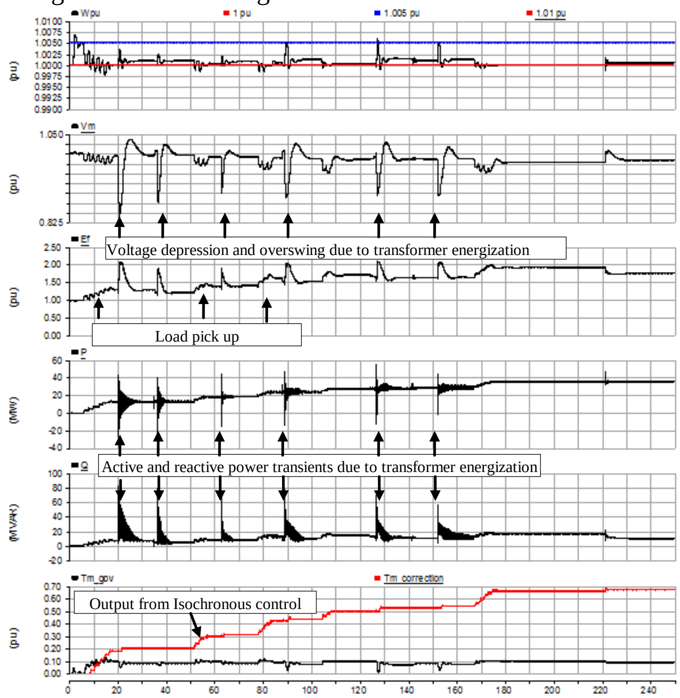

Fig. 4 Step-by-step Energization of the Island 1 with Black Start Generators loaded to 60% of Rated Capacity with Remanence

Variables that are plotted in Figure 4 to Figure 7 are listed below.

Variable Name	Description
Wpu	Machine speed
Vm	Machine terminal voltage
Ef	Machine exciter field voltage
P	Machine active power output
Q	Machine reactive power output
Tm_Gov	Machine mechanical torque
TM_Correction	Machine mechanical torque increment due to isochronous control

These cases illustrate the importance of maintaining adequate reactive margin in the system during restoration of systems with low generation, especially prior to energization of transformers. The amount of reactive margin that needs to be maintained is dependent on the composition of the load, including both steady-state power factor and dynamic behavior.

B. Self-Excitation Screening

A useful measure for assessing the likelihood of self-excitation is to determine the total length of line needed to exceed the screening criterion for self-excitation. If the calculated line length that would be needed to cause self-excitation significantly exceeds the lengths of line that are likely to be picked up with the machine then the possibility of self-excitation can be ruled out.

The minimum capacitive charging that would be required to cause self-excitation of the black start generators was calculated using machine d-axis and q-axis synchronous impedances and the generator step-up transformer leakage impedances. The minimum line charging need for self-excitation was then converted to a corresponding line length in miles assuming an average charging of 0.07 Mvar/mile for 115 kV lines.

These screening calculations indicated that the minimum line length needed to place the black start machine in Island 1 at risk of self-excitation is about 389.87 miles without negative current capability and 509.47 miles with negative current capability. For these line lengths it would virtually impossible for the black start generator in Island 1 to become self-excited.

In Island 2, if black start machine exciters do not have negative current capability, a total of 5.85 Mvar capacitive line charging (about 83.51 miles) would cause the machine to self-excite, while a minimum of 106.52 miles would be required before the machine would be at risk of self-excitation if its exciter has no negative current capability.

As these line lengths greatly exceeded the mileage of the lines in either Island system, self-excitation was not a significant risk. This is confirmed by PSCAD/EMTDC simulation.

C. Load Pickup

The pick-up of loads in a weak system with relatively low levels of generation results in a frequency impact as well as impact on the system voltage. The magnitude of the frequency and voltage impact can be limited to tolerable levels by limiting the amount of load that is picked up to about 5% of the capacity of the in-service generation.

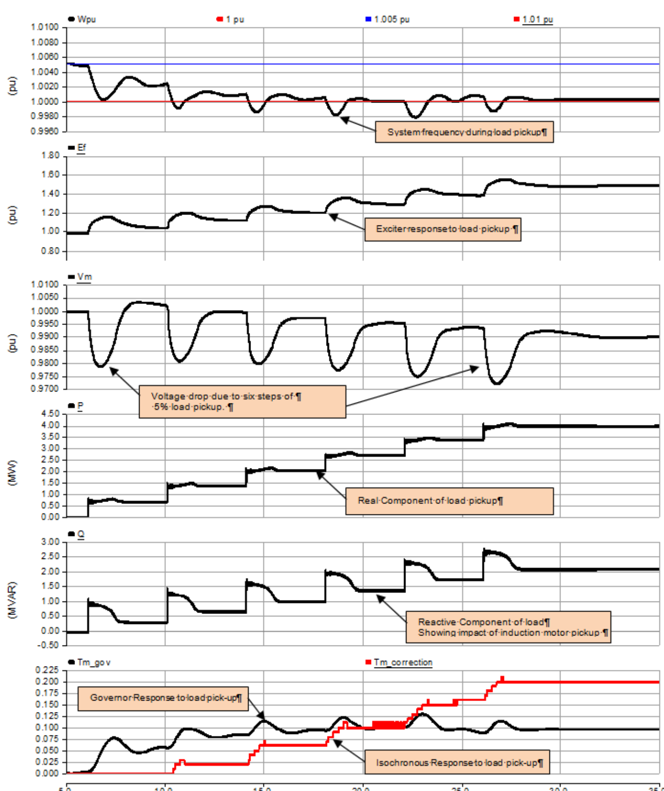

Fig. 5 Load Pick-up at Island 2 black start generator

The magnitude of the voltage change during load pick-up is influenced by the type of load being picked-up. Load pick-up on the black start generator in Island 2 is shown in Fig. 5. The load was picked up in six steps of 0.65 MW per step corresponding to 5% of the capacity of the generator.

The reactive demand of the induction motor portion of the load drops quickly as the motor speed increases reaching the steady state value in about 1.5 seconds after the load is energized.

The generator was initially running at 0.005pu fast (60.3 Hz). Each load step resulted in a frequency drop of 0.005pu or 0.3 Hz which corresponds to the expected value based on a droop setting of 5%. The isochronous frequency control loop was also in operation and its response to maintain the frequency from dropping below 60 Hz is shown by the red curve in the lowest graph of Fig.6. With the selected parameter it is able to correct the frequency deviation resulting from a 5 % load change within about 1 second.

The results indicate that a 5% load increment appears to be about the maximum that should be used for normal load pick-up as it results in acceptable frequency and voltage deviations

D. Transformer Energization

All the transformers were energized with ±80% remanence and at voltage zero crossing (worst case energization) as defined in restoration and simulation sequence. The most severe voltage sag of 36% was observed at the low voltage side of the black start generator transformer in Island 2 as shown in Fig. 6. This severe voltage drop would have an adverse impact on any loads that are already connected at the bus.

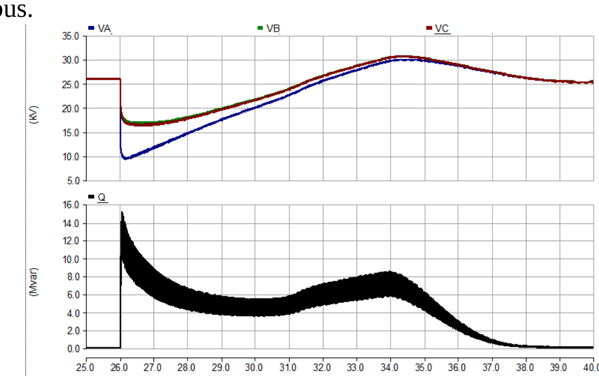

Fig. 6 Black Start Generator Low Voltage Bus Voltage Sag and Transformer Reactive Demand during Energization of Generator Step up Transformer

It would be possible to change the restoration procedure to energize the generator step-up autotransformer by connecting it prior to starting the generator. Then the transformer would be energized together with the generator under excitation control. This would avoid any inrush effects. Unfortunately this procedure cannot be followed on transformers which are not unit transformers.

The simulations of transformer energization also show the variation in reactive demand of transformers during energization of the black start generator transformer and the subsequent transformers. It was observed that

a) Transformers that are nearer the generator and which are connected earlier in the restoration sequence would have a larger inrush and larger reactive demand.

b) The decay in inrush current is much faster for the subsequent transformers compared to the generator step-up transformer. This is due primarily to the larger resistance in the circuit between the generator and the transformer being energized. This indicates that the system disturbance and the requirement for dynamic reactive margin will decrease as the distance between the generator and the transformer being energized is increased.

VI. Conclusions

The results of the simulations demonstrate that successful restoration of small systems with relatively small generators can be achieved if the necessary features are to facilitate isolated operation are provided. This would include:

(a) Ensuring that all generators have governors with droop.

(b) Designating one generator to operate in isochronous control. It should have the facility to switch back to normal droop control after connecting to an outside system.

(c) Ensuring that protections settings are suitable in the low short circuit level conditions. UV load shedding should not be set too sensitive.

(d) Disabling the automatic connection of large capacitor banks for voltage control.

(e) Communications to allow remote control of dispatch and governor control mode.

The studies also indicate:

(a) Transformer magnetizing inrush currents can cause severe voltage sag in weak system conditions but the system will recover as long as there is sufficient reactive margin available from the black start generators. Sympathetic inrush from motor loads during the voltage depression also needs to be considered.

(b) To ensure sufficient reactive margin and spinning reserve capacity for continued system expansion during restoration it would be necessary to limit the amount of load picked up to about 60% of the connected generating capacity.

(c) Switching events such as load pickup, line energization, synchronizing of generators and interconnecting the two island systems result in only system minor disturbances. However load pickup should be limited to relatively small blocks and operators need to be aware of the possibility of unexpectedly large loads due to cold-load conditions.

(d) For most systems, where line lengths are not excessive self-excitation of generators during the black start is not likely to be an issue provided that large capacitor banks are not connected. However inadvertent trip of breakers could put smaller generators at risk of self-excitation if they are left carrying a significant length of transmission line.

(e) Increased operator awareness of the operational issues and training would generally be needed for successful restoration.

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VIII. Biographies

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