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Black Start Studies

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The occurrence of a massive power outage that includes the complete loss of generation, load and the transmission network serving the system load requires the use of selected generating stations with self-starting capability to get the system back into operation. These units in themselves can only supply a small fraction of the system. Thus they need to be used to assist in the starting of larger units, which need their station service loads to be supplied outside power. Only when these larger units can come on-line can full restoration of system load occur. Thus, a restoration plan following a system blackout should include small combustion turbines or hydro turbines that can be used to black start large steam turbine driven plants located electrically close to these black starting units.

The typical black starting scenario includes the self-starting unit(s), the transmission lines that will transport the power supplied to the large motor loads in the power plant to be black started, and at least three transformer units. The transformer units would include the generator step-up transformers of the black start generating unit and the steam turbine unit involved plus one or more auxiliary transformers at the steam plant. The transmission lines used for the black start may be either overhead or high voltage underground cables. The load to be black started includes very large induction motors, ranging from a few hundred HP to several thousands HP and also plant lighting and small motor load.

The black start plan describes the steps that the transmission operators need to take to restore the isolated power system from the black start unit, sequentially energizing transformers, transmission lines, and potentially shunt compensation and load pickup, to supply power to the steam unit auxiliary loads to allow that unit to begin operation.

The purpose of a black start study is to verify the feasibility of a black start plan in terms of both steady state and transient operating conditions.

The steady state analysis of this isolated power system includes:

- Voltage control and steady state overvoltage (Ferranti effect) analysis.
- Capability of the black starting units to absorb vars produced by the transmission system connecting the plants.
- Step-by-step simulation of the black start plan being tested to ensure its feasibility and compliance with required operational limits.
- Verification of the robustness of the tested black start plan to ensure its ability to compensate for the unavailability of key components to be used in the plan.
- Generation and load matching.

Voltage control analysis determines the black starting generating unit voltage reference set-point and off-nominal tap setting for all transformers that are part of the plan. This insures proper control of voltage and that the plan will provide the needed terminal voltage to start up the large induction motor loads at the black started plant. In addition, the receiving end bus voltage of the transmission line(s) is estimated when the black starting unit energizes the unloaded generator step-up transformer and transmission line(s).

The charging current generated by the transmission system, particularly when underground cables are used to transport the power supplied by the black starting unit, can be large enough to have the black starting unit absorbing reactive power, and there could be, for extreme conditions, the potential for self-excitation. Such an undesirable operating condition may occur when the effective charging capacitive reactance of the transmission system used in the black start operation, as seen by the black starting unit, is less than the q-axis generator reactance Xq. In generating units with no negative field current capability, d-axis self excitation cannot be controlled by the excitation system, and thus the machine terminal voltage rises almost instantly. Generator excitation systems with negative field current capability delay but do not prevent the onset of self-excitation. It is worth noting that most generating units installed in the last 40 years do not have negative field current capability. Thus, it is extremely important to verify the reactive power capability of the black starting unit when operated at a leading power factor.

Another important item of the steady state analysis of a black start plan is the step-by-step simulation of a black start plan to verify its robustness to a loss of a system component and its compliance to required operational limits on voltage and power flows.

Once the steady state analysis has been completed, a dynamic analysis of the black start plan follows. The dynamic analysis starts from an initial steady state operating point representing a step in the plan. This initial system operating condition is usually obtained from the system steady state analysis. One key simulation starts from the state of the isolated power system prior to the start up of the largest induction motor load and simulates the starting of that motor.

The dynamic analysis of a black start plan includes some or all of the following analyses:

- Load-frequency control
- Voltage control
- Load rejection – voltage and frequency dynamics
- Self-excitation assessment
- Large induction motor starting
- Motor starting sequence assessment
- System stability

The dynamic analysis of the restoration plan simulates the start up of the large induction motor load, such as boiler feed-water pumps and draft fans, and assesses the load frequency response observed during the start up.

The frequency dip and recovery produced by the start up of the largest motor is one of the results sought from this analysis. The frequency dip is used to ensure that tripping of the black starting unit by under-frequency protection does not occur. The frequency recovery response might also help in the selection of the most technically viable motor starting sequence.

The large voltage dip caused by the start up of large induction motor load is also assessed in the dynamic analysis of a black start plan. This pronounced voltage dip may cause magnetic contactors used with motor load to drop out, tripping important motors, or may result in those motors staying on-line to stall. The failure to keep the motor load running will lead to a failure of the black start plan and the steam unit will not be started.

Another important result from this dynamic voltage analysis is the assessment of the reactive power capability of the black starting unit to supply the large reactive component of the starting current. This reactive power is in addition to the reactive power being supplied to the black started plant to feed its auxiliary lighting and small motor load. The voltage recovery response observed during the start up of the large induction motor load is used in assessing the adequacy of the starting motor thermal protection based on its maximum acceleration time. The operating condition of a partial or full load rejection due to a sudden loss of the motor load due to an undervoltage condition can also be studied here. This type of analysis will help evaluate the overfrequency, volts/Hz and overvoltage protection of the black starting unit.

It is important to show not only that each of the large induction motors can be started successfully, but also that they can be started in the sequence required for correct plant operation. So for example, to test the start up of the second motor in the sequence, a load flow base case is prepared where the first motor in the starting list is running and the starting of the second motor is simulated. This tests both the ability of the starting motors to start but also the running motors to remain in operation. This process progresses through the starting sequence.

Finally, system stability is checked to make sure that voltage and rotor angle stability are maintained during the implementation of the black start plan. Angular stability is assessed only when more than one generating unit is used in the black start plan. Otherwise, frequency stability is what matters in the stability assessment of the plan.

Another important analysis regards the transient overvoltages that may result from energizing transmission lines, cables and transformers. These transient overvoltages can be either short duration switching surges or longer duration temporary overvoltages. Switching surge overvoltages typically recede to normal steady state levels within a few cycles of the fundamental frequency while temporary overvoltages can last several seconds. The energizing of transformers during black start conditions can result in harmonic rich currents that can resonate with system impedances to produce temporary overvoltages. These temporary overvoltages can lead to equipment failure or damage that may hinder the successful implementation of the black start plan. The software tool used for this type of analysis is the electromagnetic transient program (EMTP) where a distributed parameter model for transmission lines, saturation effects in transformer models, a fixed voltage source model for generating units and surge arrester models are included. See the companion article “Temporary Overvoltages Following Transformer Energizing”.

Siemens PTI has performed several such black start analysis studies recently for both rural and large city systems.