An Overview of Restoration Issues and Blackstart Analysis

Carlos Grande-Moran
Phone: 518-395-5084
Fax: 518-346-2777
carlos.grande@siemens.com

James W. Feltes
Phone: 518-395-5083
Fax: 518-346-2777
james.feltes@siemens.com

Siemens Power Technologies International Inc.
Consulting Services
400 State Street
Schenectady, New York 12305

I. Introduction

Modern power systems are operated to withstand the variability in system conditions that occur during normal operation such as daily changes in load levels, generation dispatch and network's facilities availability. These systems must also provide reliable service to loads for unusual events, such as faults and the tripping of transmission lines or generating units. However, extreme events can occur which may lead to a partial or total system blackout. Thus the ability to recover from such catastrophic events is necessary and utilities have the responsibility to develop detailed restoration plans and procedures to restore the power system safely, efficiently, and as expeditiously as possible. This paper gives a brief overview of many of the issues involved in power system restoration and blackstart analysis.

Power system restoration issues can be broken up into regulatory, economic, and technical issues. The emphasis in this paper will be given to the technical issues associated with the restoration of a power system following a partial or total blackout and only a brief overview of the first two issues will be provided.

Regulatory issues are associated with the directives from authorities in charge of determining the required level of service reliability to be supplied by the utilities to the end users. As part of this process, the regulatory authorities generally establish criteria and requirements for power system restoration. In the USA, standards and criteria are established by the North American Electric Reliability Corporation (NERC), the Nuclear Regulatory Commission (NRC), the NERC regional authorities, state public service commissions and other state agencies and the local independent system operator (ISO) or regional transmission operator (RTO). While the regulatory process and requirements are different in other parts of the world, the fundamental concepts are generally quite similar.

The NERC requirements are delineated in the Emergency Preparedness and Operations (EOP) standards. The standards that cover the areas being discussed here are EOP-001 - Emergency Operations Planning and EOP-005 - System Restoration from Blackstart Resources. EOP-001 covers the requirements to develop, maintain, and implement a set of plans to mitigate operating emergencies. The purpose of EOP-005 is to ensure that plans, facilities, and personnel are prepared to enable system restoration from blackstart resources, to ensure that reliability of cranking path(s) is maintained during restoration and that high priority is placed on restoring the blacked out network and interconnection to neighboring power systems.

Economic issues are handled in different ways not only within the US but also throughout other parts of the world. In the traditional vertically integrated utility structure, the utility was responsible for generation, transmission, and distribution, and hence all the system components required for restoration. In a market based system, however, coordination of many parties is required, as different owners and operators for the generators, the transmission system and the distribution systems are involved. Common to both structures is the need to set clear requirements and compensation of the participants for fulfilling these requirements. This is often a complicated process. Similar to expenditures for life and medical insurance, one needs to spend money on something that one hopes to never actually use. Also, it is quite hard to measure the quality of restoration services until it is tried following a partial or total blackout. We will not delve any further into these issues here other than to state that system restoration is a critical service and that the incentives for generation and transmission owners must be sufficient for them to not only offer these services but to diligently participate in the necessary testing and training required to implement them successfully when needed.

The main focus of this paper is on the technical issues that impact power system restoration.

General Principles

Most outages are local events, and restoration of the outaged system is handled by the local utility, sometimes with assistance from neighboring utilities. Outages involving larger geographic areas are less frequent, but require more complex restoration procedures. Most of these outages involve only a portion of the power system that can be restored with assistance from neighboring power grids. While such restoration can be a complex process, the restoration generally occurs in a relatively straightforward manner. First the tie lines from the outside power system to the blacked out network are energized to establish one or multiple cranking paths. These ties are the starting points used to energize the transmission system. With significant circuits in the transmission network energized, it is relatively straightforward to pick up the sub-transmission system, start restoring some of system load, and supply auxiliary power to selected power plants to bring available generation back on-line. This is an example of a *top-down restoration*, where, the bulk transmission grid is energized first and used next to energize the lower voltage networks.

However, in the case of a wide spread blackout, there may not be help readily available from neighboring systems. In this case, system restoration must begin from pre-selected generating units with the ability to start-up themselves, i.e., without requiring any external sources. These units, generally called blackstart units or blackstart resources (BSRs), are then used as the kernels to start the restoration process. This is an example of a *bottom-up restoration*, starting from an individual generating unit and emanating outward towards the critical system load by energizing the sub-transmission network first and the bulk transmission network later. Of course to speed up the restoration process, this blackstart sequence will likely be occurring simultaneously using several blackstart units independently, where these independent islands consisting of generation, network (cranking path) and load will later be synchronized to restore the original power system. Generally in a bottom-up plan, the BSRs are relatively small generating units, usually hydroelectric, gas turbine, or diesel power plants. Due to their size, these units are not able to restore the majority of the load, but are used to supply power to larger generating plant to enable them to start, i.e., they supply the "cranking" power to the larger units. The EHV grid and the majority of the load can only be restored after these larger plants are on-line.

Restoration can, certainly, be a combination of the above approaches. Starting from an individual generating unit and energizing lines in the bulk transmission system first followed by the use of the sub-transmission network to reach selected power plants is another type of *top-down restoration.* As will be discussed in more detail later in this article, energizing lines in the bulk transmission system first is more difficult and will usually require larger generating units to be on-line. However, if a cranking path can be successfully established, it will generally lead to a faster start-up of selected generating plants and restoration of critical system loads.

Restoration Plan and Procedures

Restoration plans and procedures must be developed by all transmission system operators, clearly delineating the actions to be undertaken and the responsibilities of each of the parties involved in the restoration process. These procedures must meet established reliability criteria and be able to be implemented by system operators at a central control center or local control center, or both.

Restoration plans define the sequence of steps and cranking paths needed to restore power to critical loads and generation facilities from BSRs. Ideally, the BSRs are able to start quickly and energize secure transmission paths. A backbone network is formed so that critical load can be restored, particularly stabilizing loads for the BSRs and auxiliary loads at destination power plants.

The restoration plan focuses on restoring the key system elements (generating stations, transmission lines, substations, and loads) that facilitate restoration of additional facilities. In particular, flexibility is important because major equipment may be out of service and not be available to assist in the restoration process. For example, restoration of a generation plant or substation with multiple transmission outlets is preferable to a location with a single path. This also illustrates the need for simplicity in a plan, as the more complex a plan is, the more chances a key component or action cannot be performed when or in the manner required.

In order to be able to fully restore the system, the restoration plan must be able to reenergize the transmission system to major generating facilities in a timely manner and also reach interconnection points with neighboring systems to form a larger and usually more stable grid. The supply of off-site power to nuclear power plant auxiliary systems is also a priority for those systems with nuclear generation.

The restoration plans and procedures must also address a large number of other topics including:

- Detailed documentation of each cranking path in the restoration plan. This documentation should include detailed, step-by-step description of the energization sequences including the equipment to be switched at each step and any pre-switching requirements (e.g., generator voltage setting adjustments, checking of shunt reactor or capacitor bank status, etc.)
- Staffing and communication requirements
- Training of control center staff and field staff needed to perform switching operations and energization of key transmission equipment
- Communication protocols among control centers and transmission and generation facility operators
- Requirements of the BSR units including technical issues such as voltage and frequency control capabilities and managerial issues such as maintenance and adequate fuel supply capability
- Testing of the plans including the starting of BSR units and drills testing the communication and coordination of the various power system operators.

Blackstart Analysis

As noted above, each transmission operator is required by NERC and other regulatory agencies to have plans, procedures, and resources available to restore the electric system following a partial or total shut down of the system. The standards also require each transmission operator and balancing authority to verify their restoration procedure by actual testing or by simulation.

Restoration testing is a complex process. Testing of blackstart units requires starting and running the units for a limited period of time. This is generally a relatively straightforward procedure. The coordination of the test period, however, is complicated by considerations of staffing requirements, environmental emission restrictions when combustion turbines are selected as BSR units, and the overall system requirements. Testing of line energization is more complex, as it involves de-energization and isolation of parts of the transmission system such that they can be connected to the blackstart unit. This must be accomplished without adverse impact to loads used in the plan. This may not always be possible. Restoration plans that require the energization of selected load at a particular step in the plan cannot be tested beyond that step because it is never acceptable to submit loads to outage and pickup as part of a test. Thus simulation is usually required to verify and validate the plan in addition to any field testing performed, so a study including both steady state and transient analysis is generally performed.

The restoration plan must document the cranking paths. For example, the plan show the number and switching sequence of transmission elements involved, including the initial switching requirements between each blackstart generating unit and destination power plants.

In the case of a total blackout, system restoration must begin from the blackstart unit(s), restoring the power system outward towards critical system loads. As the blackstart units themselves can only supply a small fraction of the system load, these units must be used to assist in the starting of larger units, which need their station service loads to be supplied by outside power sources. Full restoration of system load can only occur when these larger units can come on-line. Thus, the restoration plan following a system blackout should include self-starting units that can be used to blackstart, for example, large steam turbine driven plants or gas turbines that are part of combined cycle (CC) plants located electrically close to these units. Another objective for many systems is the supply of auxiliary power to nuclear power stations in need of off-site power to supply critical station service loads. Other priority loads may include military facilities, law enforcement facilities, hospitals and other public health facilities, and communication facilities.

The typical restoration scenario includes the blackstart (self-starting) unit(s), the transmission lines that will transport the power supplied to system loads and large motor loads in the selected destination power plants, and at least three power transformer units. These three transformer include the generator step-up transformer of the blackstart generating unit, the generator step-up transformer of the unit to be blackstarted and one or more auxiliary transformers serving motor control centers (MCC) at the destination power plant(s). The transmission lines used in a blackstart plan may be either an overhead line(s) or high voltage underground cable(s). The load picked up in the cranking path may include includes load from feeders at distribution substations and the lighting, small motor load and very large induction motors, ranging from a few hundred horsepower (HP) to several thousands of HP at the destination plant(s).

The key concerns are the control of voltage and frequency. Both voltage and frequency must be kept within a tight band around nominal values to guard against damage to equipment and to ensure progress in the restoration process. Any equipment failure will severely hinder the restoration process and may require starting over with a revised plan. System protection operations can also occur if voltage or frequency goes outside acceptable ranges, again with the potential to set back or stop the restoration process. The following sections give an overview of several of the technical concerns that must be addressed.

Steady State Analysis

The restoration plan describes the steps that transmission operators need to take to restore the outaged power system with assistance from the blackstart unit(s). This includes sequentially energizing transformers, transmission lines and potentially shunt reactive lagging compensation and available system load with the goal of supplying power to auxiliary loads at selected destination plant(s) to start up generating units. Once generating units are available, transmission lines can be energized, again in a step by step sequence, to supply power to major substations where load can be picked up and further interconnections made until the grid is fully restored.

The steady state analysis of this isolated power system includes:

- Analysis of voltage control and steady state overvoltages following line energization (Ferranti effect). Voltage control is applied using the reactive power capability of blackstart units, system load and when available reactive lagging shunt compensation (reactors) and under load tap changing in transmission transformers.
- Confirmation of the capability of the blackstarting units to absorb the reactive power (vars) produced by the charging capacitance of the transmission system.
- Step-by-step simulation of the blackstart plan being tested to ensure its feasibility and compliance with required operational limits.
- Verification of the robustness of the tested blackstart plan to ensure its ability to compensate for the unavailability of key components to be used in the plan.
- Demonstration of generation and load matching capability.

Through step-by-step simulation of the restoration sequence, the voltage control analysis determines for each stage of the cranking path the voltage reference setpoint of the blackstart generating unit(s), the minimum load at distribution substations, and when allowed the off-nominal tap setting for all transformers that are part of the plan. Adjustment to the voltage reference setpoint of the automatic voltage regulator ensures proper control of blackstart unit terminal voltage, keeps transmission system voltages within limits and provides the needed terminal voltage at destination plant(s) to start up the large induction motor load. Transformer tap settings that are appropriate for normal conditions, generally having significant current flows, may result in high system voltages under the lightly loaded blackstart condition. Since most taps on generator step-up transformers and station auxiliary transformers cannot be changed under load, the selection of transformer taps must be a balance between the needs of the blackstart period and normal operation when the power system is supplying a significant amount of load. However, transmission transformer units with under load tap changing capability can be set to tap positions that will allow power system operators to help control voltage in the cranking path.

Load flow simulations can be used to calculate the receiving end bus voltage of the transmission line(s) when the blackstart unit energizes the unloaded generator step-up transformer and transmission line(s). The charging current generated by an unloaded transmission line will result in a rise in voltage along the line. This is particularly true when underground cables are used as they have significantly more charging capacitance. The charging requirements can be large enough to result in the blackstart unit absorbing reactive power. There could be, under extreme conditions, the potential for self-excitation of the blackstart unit. Self-excitation is discussed in a following section of this paper.

The steady state analysis of a restoration plan should include a step-by-step simulation of the plan to verify its compliance with required operational limits for voltage control and power flows. The robustness of the plan for the loss of a system component is also valuable knowledge because the events leading to the blackout could result in some equipment unavailability during the restoration period. Generally, thermal overloads are not a restoration issue because the system is lightly loaded. Thermal overloads may become a concern, however, as restoration progresses and load is picked up along the cranking path.

Dynamic Analysis

Once the steady state analysis has been completed, a dynamic analysis of the restoration plan is conducted. The dynamic analysis starts from an initial steady state operating point representing a step in the plan. The initial system operating condition(s) used in the dynamic analysis is usually obtained from the system steady state analysis. One key simulation uses the isolated cranking path up to the largest motor load terminals to simulate the start up of the largest induction motor load at the selected destination plants. This verifies that the voltage supply is strong enough to start the motor and also that the voltage dip will not stall or cause the motor contactors of running motors at the destination plant to drop out.

The importance of accuracy in equipment modeling must be emphasized. The effect of the controls of an individual unit is generally not very significant under normal operation because a large number of units are sharing the control of system voltage and frequency. However, both of these quantities are controlled solely by the blackstart unit during the initial restoration period. Thus, the modeling of the generator, excitation system and speed governor is very important. The modeling of equipment that does not generally operate under normal conditions such as over- and under-excitation limiters and volts/Hz protection can also be important. Governor modeling must take into account whether the machine is operated in an isochronous or droop control mode, as will be discussed later. The accuracy of dynamic modeling parameters of any large motors to be started are also important to motor starting simulations.

The dynamic analysis of a blackstart plan includes some or all of the following functions:

- Load-frequency control
- Voltage control
- Load rejection
- Large induction motor starting
- Motor starting sequence assessment
- Self-excitation assessment
- Cold load pickup
- System stability
- Switching transient overvoltages

Because frequency may deviate significantly from its nominal value, the effect of frequency variation on system impedances and loads must be modeled.

Blackstart Units

As noted above, blackstart units (blackstart resources) are units that do not require off-site power to start. Generally these fall into four categories:

- **Hydroelectric units**. These units can be designed for blackstart capability and have fast primary frequency response characteristics and a steep ramping rate capability.
- **Diesel generator sets**. Diesel sets usually require only battery power to start and can be started very quickly. They are small in size and useful only for supplying the power needed to start larger units. They generally cannot be used to pick up any significant transmission system elements.
- **Aero-derivative gas turbine generator sets**. This type of gas turbine typically requires only local battery power to start. These units can usually be started using remote commands and can pick up load quickly. They require a minimum load before energizing any significant transmission system elements.
- **Larger gas turbines operating in a simple cycle mode and steam turbine units**. These units are not in themselves blackstart capable, but are coupled with on-site diesel generator sets to make the plant a blackstart source. The diesels are started and used to energize plant auxiliary buses and start either the gas turbine or steam turbine. A gas turbine is generally quicker to bring on-line. The time to restart and available ramping capability is generally a function of how long the unit was off-line. They require a stabilizing (i.e., minimum) load before energizing any significant transmission system elements.

Load-Frequency Control

When only a portion of the system is lost and is being restored using ties to the larger system, load-frequency control is not generally a large concern. The outside system generally has the capacity to absorb changes in load without significant frequency deviations.

However, when restoration without external resources is required, load-frequency control is of critical importance. During the restoration process, the blackstart generating unit will typically be used to pick up large induction motors, e.g., boiler feedwater pump, forced draft and induced draft fan motors associated with a larger steam power plant. The frequency in the electrical island will be controlled by the speed governor of the turbine driving the synchronous generator of the blackstart unit.

It is standard practice in multi-machine power systems with units operating in parallel that all prime movers supplying mechanical power to the generators coupled to these units should be operating in a droop governing mode. This provides a stable sharing of the electric system load among all units. However, because of the proportional characteristic of the droop speed governor control, a steady state frequency error will remain in the system. Supplementary frequency control, also called automatic generation control (AGC), has the form of a pure integral controller and will follow the primary frequency control action of the speed governors to remove this undesirable steady state frequency error. Typical steady state regulating droop (R) for speed governors is 5% on a system frequency base of 50 Hz or 60 Hz and turbine MW rating base power.

However in blackstart plans it is imperative that system frequency regains its scheduled value following the start up of motors or pick up of any system load. This frequency control should preferably be automatic to minimize the potential for undesirable operating errors. The automation of the frequency control process can be carried out by the prime mover speed governor operated in a constant frequency or isochronous control mode. In this pure integral control mode, the steady state frequency error is zero because of the resetting characteristic of the pure integral control. Most, if not all, modern diesel engines, gas turbines and hydraulic turbines are furnished with digital speed governors where a selection of either a droop or isochronous operating mode is carried out by a simple change in command.

Once the system has more than one generating unit on-line, all speed governors should be operated in a droop control mode, unless it is decided in the restoration plan that one of the largest units will operate in isochronous control more to maintain the control of the system frequency. Note that the supplementary frequency control (AGC) will be disabled under this extreme condition.

In summary, the preferred control mode for speed governors associated with blackstart unit is isochronous or constant frequency control. When additional units are added, the preferred control mode for speed governors is droop control mode. In some cases, it may be preferable to keep one large unit in isochronous control mode. Units should not be operated in parallel with more than one unit in isochronous control mode.

Voltage Control

Control of voltage is obtained through the generator’s excitation system. The excitation system must be operated in automatic control, that is, with the automatic voltage regulator (AVR) in service. The system voltage will be a function of the generator terminal voltage. Thus, the generator scheduled voltage may need to be adjusted throughout the restoration process, as load is picked up, and also coordinated with any changes in transformer tap positions in the cranking path. Such adjustments should be an integral part to the restoration plan. The changes in voltage that will be seen upon the starting of large motors or the pickup of large blocks of load require that the excitation system respond in a quick, well-tuned manner.

Load Rejection

In the early stages of the restoration process, the system can be operating in a state where loss of a single system component results in the outage of some of the connected load. The impact of loss of load on frequency and voltage in an electrical island consisting of the blackstart plant, cranking path and destination plant(s) is usually evaluated using the following operating scenarios:

- Loss of the largest block of loads in the electrical island. Because of the large increase in frequency and voltage in the electrical island, the modeling of the electrical island should also include the effect of both voltage and frequency on the system impedances and loads.
- Loss of load at some intermediate step in the cranking path. This event is simulated to estimate a frequency range over which frequency and voltage would rise due to the loss of load. It should also include the effect of frequency and voltage on the system impedance and loads.

The results of these dynamic simulations help estimate the fundamental frequency overvoltage and overfrequency condition caused by the loss of large blocks of load in an electrical island. These results are then used to verify settings of overvoltage relays and overspeed protection for blackstart units. The expected bus voltage recovery times in the island and the voltage response time of the blackstart unit excitation system are obtained from this analysis.

Motor Starting

A blackstart unit's primary function is generally to start up the auxiliary load of a larger power plant. Thus motor starting at this larger destination plant is a primary concern during blackstart restoration. The auxiliary load of the destination plant is made up of lighting and motor load used, for the most part, in the start up of steam generators and fuel systems. The motor load is made up of a large number of small and medium size horsepower (HP) motors and a few large HP motors ranging anywhere from several hundred HP and up to several thousand HP. Fuel and feed-water pump motors and forced and induced draft fan motors are examples of this large HP group. It is this latter group which presents the greatest challenge to the reactive power resources available in any well-designed restoration plan.

The method used for starting up these large motors is often across-the-lines, that is, a hard start. In some cases, the motors may be soft started, that is, started at reduced voltage. Thus, it is extremely important to properly identify the motor starting method since this will greatly impact the depth of the dip in voltage seen during the startup of selected destination plants in a restoration plan.

It is also very important to gather motor data that will assist the analyst conducting dynamic studies to verify the viability of a given motor starting process. The information needed to establish the dynamic model for the large induction motors participating in the motor starting process includes: motor plus mechanical load inertia, starting or locked rotor torque, starting or locked rotor current and associated power factor, pull-out torque, full-load torque, full-load current and associated power factor. All of these data should be at rated voltage and frequency. From this motor performance data, parameters for the stator and rotor circuits of the motor are estimated. The dynamic model for these large induction motors should include both inertial and rotor circuit flux dynamics. Verification of this dynamic model must result in a close matching of the speed-torque characteristic, particularly at starting, pull-out and full-load operating points. In addition, it is important to include the mechanical load damping effect in the inertial model of the mechanical load, which for most centrifugal pumps and fans follows a quadratic speed-torque characteristic.

The motor starting sequence is another variable that must be verified in any blackstarting process. Feasibility of the plant startup can be tested by a dynamic simulation of the various motor starting sequences. The sequence must also accommodate the startup requirements of the plant, which may require certain motors to be started before others.

The voltage dip caused by the starting of these large induction motors must also be accurately quantified because magnetic contactors used by the already on-line motors open up generally around 80% of their terminal voltage. The IEEE Standard 399-1997 recommends a minimum terminal voltage of 80% of rated voltage. Occasionally there may be magnetic contactors that can hold their contacts for voltages as low as 70%; however, the number of cycles that this operating condition can be sustained is low. In addition, the life expectancy of the insulation of the stator and rotor windings is reduced as a result of the large inrush currents circulating through these windings. In situations where this is found, the motor manufacturer must be consulted to avoid a catastrophic failure at worst or shorted turns at best. Undervoltage protection settings should also be verified to avoid opening of circuit protection caused by undervoltage relay action.

The acceleration time period required by an induction motor depends in great measure on the combined inertia of the motor and its mechanical load. The longer the accelerating period, the higher the heating experienced by the stator and rotor windings. When accelerating periods last a few tens of seconds, motor manufacturer data on allowed motor heating should be consulted to avoid a significant loss of useful operating life of the winding insulating material.

Self -Excitation

As noted above, energization of an extra-high voltage (EHV) transmission line or cable will result in a rise in voltage along the line or cable due to charging currents. The charging requirements can be large enough to result in the blackstarting unit absorbing reactive power. There is the potential for self-excitation if the charging vars are high relative to the size of the generating unit. The result can be an uncontrolled rise in voltage and could result in equipment failure. Such an undesirable operating condition may occur when the per unit effective charging capacitive reactance of the transmission system used in the blackstart operation, as seen by the blackstarting unit, is less than the per unit q-axis generator reactance $Xq^* \omega$, where ω is the per unit generator speed. 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 for cases where the capacitive reactance is less than the per unit d-axis reactance $Xd^*\omega$. Generator excitation systems with negative field current capability delay but do not prevent the onset of d and q-axes 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 blackstarting unit when operated at a leading power factor.

Self-excitation can also occur from the load end through inadvertent loss of supply, with the opening of a transmission line or cable at the sending end, leaving the line connected to a large motor or a group of motors.

Cold Load Pickup

The purpose of the restoration process is, of course, to restore the power supply to the loads and allow them to operate in a manner similar to that which existed prior to the outage. However, the characteristics of the load immediately after re-energization may be quite different than the characteristics exhibited prior to the outage.

If the load has been de-energized for several hours or more, the inrush current upon re-energizing the load can be as high as eight to ten times normal the normal load current. The magnitude and duration of the inrush current that flows when a feeder is re-energized after a prolonged outage is a function of the type of load served by the feeder. This could include lighting, motors, and also thermostatically controlled loads such as air-conditioners, refrigerators, freezers, furnaces, and electric hot water heaters.

There are different components of the load which contribute to the total inrush current. An example is the component due to the filaments of incandescent lights. The resistance of the filament is very low until it warms to operating temperature. This low resistance results in a very high inrush current – up to ten times normal. This high current flows for a short period, approximately one-tenth of a second.

Another component of the inrush is due to the starting of motors when the load is picked up. When a motor starts, the current drawn will be typically five to six times normal, until the motor accelerates up to its operating speed. This may take as long as several seconds for large industrial type motors.

A third component of inrush current is that due to thermostatically controlled loads, which turn on and off automatically to hold temperature to a desired, preset value. Under normal operating conditions, only about one-third of these loads will probably be connected at any instant in time. But after a lengthy interruption of service, they will all have their thermostat contacts closed, waiting to run as soon as power is restored. As a result, these thermostatically controlled loads will be perhaps three times greater than they normally would be for the first half hour or so after being energized. Most thermostatically controlled load also contain small single phase motors, which will draw five or so times running current until they are accelerated up to running speed in perhaps a half second. Thus, the initial current drawn by some thermostatically controlled loads could be as high as fifteen times normal current for the first half second following energization of feeders supplying this load.

A summary of the magnitude and duration of inrush current for some of the various types of loads is shown in Figure 1.

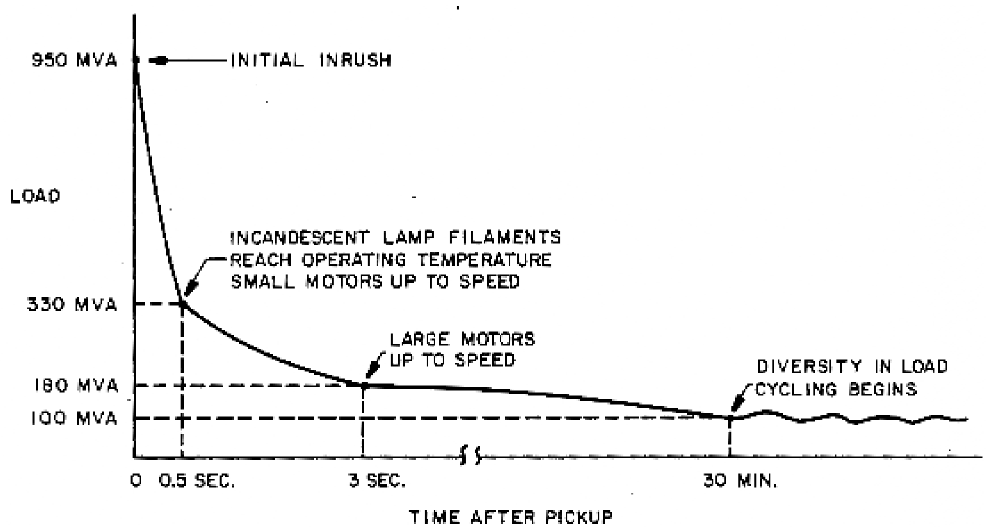

Figure 1. Load Variation Following Cold Load Pickup

System Stability

Power system stability is defined as "the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact".[1] Basically this simply

[1] IEEE/CIGRÉ Joint Task Force on Stability Terms and Definitions – "Definition and Classification of Power System Stability", IEEE Trans. on Power Systems, vol. 19, no. 2, May 2004, pp. 1387-1401

means that the power system must be able to survive the disturbance and return to a sustainable operating condition without significant loss of equipment.

Power system stability can be further subdivided into:

- rotor angle stability – the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance
- voltage stability **-** the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance
- frequency stability **-** the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load.

The latter two types of stability were previously discussed above, looking at the aspects of voltage and frequency control most of concern during restoration. Angular stability is generally not a major concern in the early stages of the restoration process. When the system is being restored from a total blackout, angular stability is assessed only when more than one generating unit is used in the blackstart plan. Even when there are multiple units involved, it must be noted that in the early stages of a restoration plan, the system is operating in a weakened state. Whereas there are generally multiple transmission paths between groups of generation such that a fault and trip of one of these paths does not result in instability, during restoration there may only be one strong path and hence a fault and outage of that path would cause instability. However, this period of exposure cannot limit the restoration but it is simply a stage in the process leading to a more robust stage. The exposure to instability can be used as one of the criteria to rank restoration alternatives.

Switching Transient Overvoltages

Restoration of the power system is performed through a series of switching actions to sequentially reenergize the system components. Energizing equipment during restoration conditions can result in higher overvoltages than during times of normal operation. These overvoltages can lead to equipment failure or damage that may hinder the successful implementation of the restoration plan.

Transient overvoltages include temporary overvoltages, switching surges and lightning surges. Lightning surges, while an important design consideration, are not a concern that impacts the restoration of a power system.

Switching surges are the transient overvoltages that immediately follow the opening or closing of a circuit breaker or other switching device. Switching surges have high frequency (100 Hz to 10 kHz) components that decay quickly, typically within two to three cycles of the power frequency, and are followed by a normal steady state voltage. Switching surges typically contain only one, or just a few, voltage peaks that are of interest, as shown in Figure 2. This sample waveform is from a simulation of the energizing of a typical overhead line.

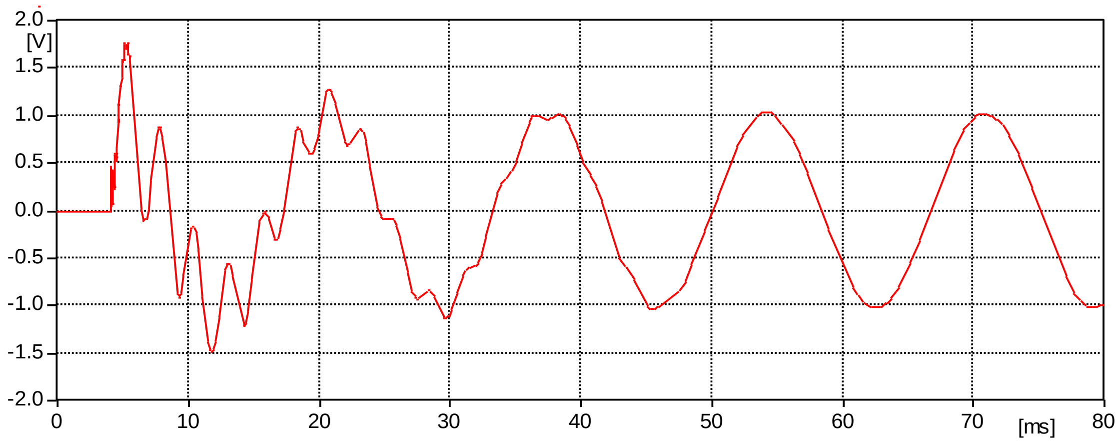

Figure 2. Example of a Switching Surge from an Electromagnetic Transient Program Simulation of the Energizing of a Typical Overhead Line.
The voltage is in per unit of the nominal peak phase voltage rating.

The magnitude and waveshape of the switching surge depends upon the angle of the power frequency source voltage wave at the instant of circuit breaker closure. This requires that many simulations be performed with various closing times to obtain a statistical distribution of the overvoltage results. Surge arresters are effective in limiting the peak of the switching surges.

Temporary overvoltages (TOV) includes many types of events where the voltage transient lasts longer than the surges discussed above, exceeding the rated voltage value for three cycles and potentially significantly longer. TOV encompasses power frequency phenomenon such as the Ferranti rise on an open-ended line or cable and the overvoltage on an unfaulted phase during a single line to ground fault.

Temporary overvoltages can also follow switching surges. For example, a TOV can result from switching circuits that saturate the core of a power transformer, such as when cables or EHV overhead lines and transformers are energized together. The harmonic rich transformer inrush currents can interact with the harmonic resonances of the power system. The resonant frequencies are a function of the series inductance associated with the system's short circuit strength and the shunt capacitances of the cables and lines. Higher inductances (relatively weak systems, such as those often occurring during restoration) and higher capacitances (long cables) yield lower resonant frequencies and a higher chance of TOV.

Figure 3 shows an example of a temporary overvoltage taken from a simulation of the energization of a large transformer. Like switching surges, this type of temporary overvoltage can be dependent upon the circuit breaker closing times. In contrast to switching surges with one predominant peak, temporary overvoltages can have hundreds of peaks of about the same magnitude if the TOV duration is several seconds.

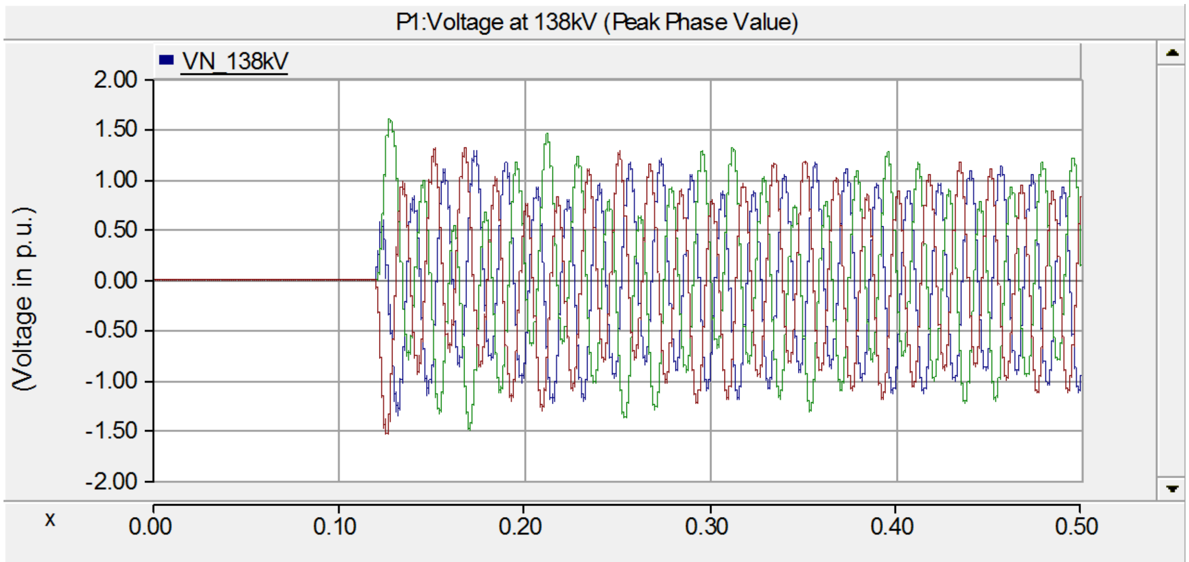

Figure 3. Example of a Temporary Overvoltage in Per Unit of Nominal Peak Phase Voltage Rating

The expected TOV magnitude and duration is often a major concern for surge arresters. MOV type surge arresters have little effect upon temporary overvoltages that are about below 1.6 per unit. Silicon carbide type surge arresters are not affected by TOV levels below the 60 Hz sparkover level. However, if the TOV repeatedly exceeds the sparkover level, then the multiple discharges may result in excessive energy absorption and arrester failure.

Blackstart Analysis Example

An example of a dynamic simulation of motor starting analysis is presented in this section. The scenario is one where a fast starting gas turbine driven generating unit is used as a blackstart unit to start up a combined cycle power plant. The model of the power system includes the generator step-up transformer of the blackstart unit and the generator step-up and auxiliary transformers at the destination plant. These plants are connected by overhead EHV lines. The tap settings in all transformers with tap adjustment capability and the voltage reference setpoint of the blackstart unit were set to ensure that the terminal voltage at the large induction motor units used in the motor starting process was initially slightly above its nominal value to help accommodate the voltage dip seen during the start.

The motor starting sequence at the destination plant begins with the across-the-line starting of a 2750 HP motor with about 6 MW of lighting and running motor load already on line. The motor performance during the starting period is shown in Figure 4. Terminal voltage, motor reactive power, electrical torque and motor slip are shown. Note the dip in motor terminal voltage and that the demand for reactive power increases during the period following the lowest voltage at the motor terminals. The minimum voltage at the motor terminal is about 81.5%. The air gap torque increases significantly during the acceleration period, as expected, to overcome the mechanical load torque opposing the developed electromagnetic torque. The motor takes about 9 seconds to reach its operating speed.

The dynamic response of the blackstart unit during the starting of the large induction motor is shown in Figure 5. The reactive power output of the generator increases to supply the large reactive demand of the starting motor. This results in a dip in the generator terminal voltage. The performance of the excitation system is shown as it works to control the blackstart unit terminal voltage. Note the fast response and large field forcing capability to pull up the machine terminal voltage from the dip caused by the large reactive power demand imposed by the starting motor. The unit also sees a significant voltage rise caused by the rapid reduction in reactive power as the motor locks in to its operating speed. Electric power demand also increases during the starting period as the motor is accelerating and moving towards its steady state operating point. There is a drop in frequency due to the electric power demand of the starting motor which is compensated for by governor action increasing the mechanical power of the gas turbine. Note that similar to the voltage, there is also a rise in frequency caused by the rapid change in real power as the motor locks in to its operating speed.

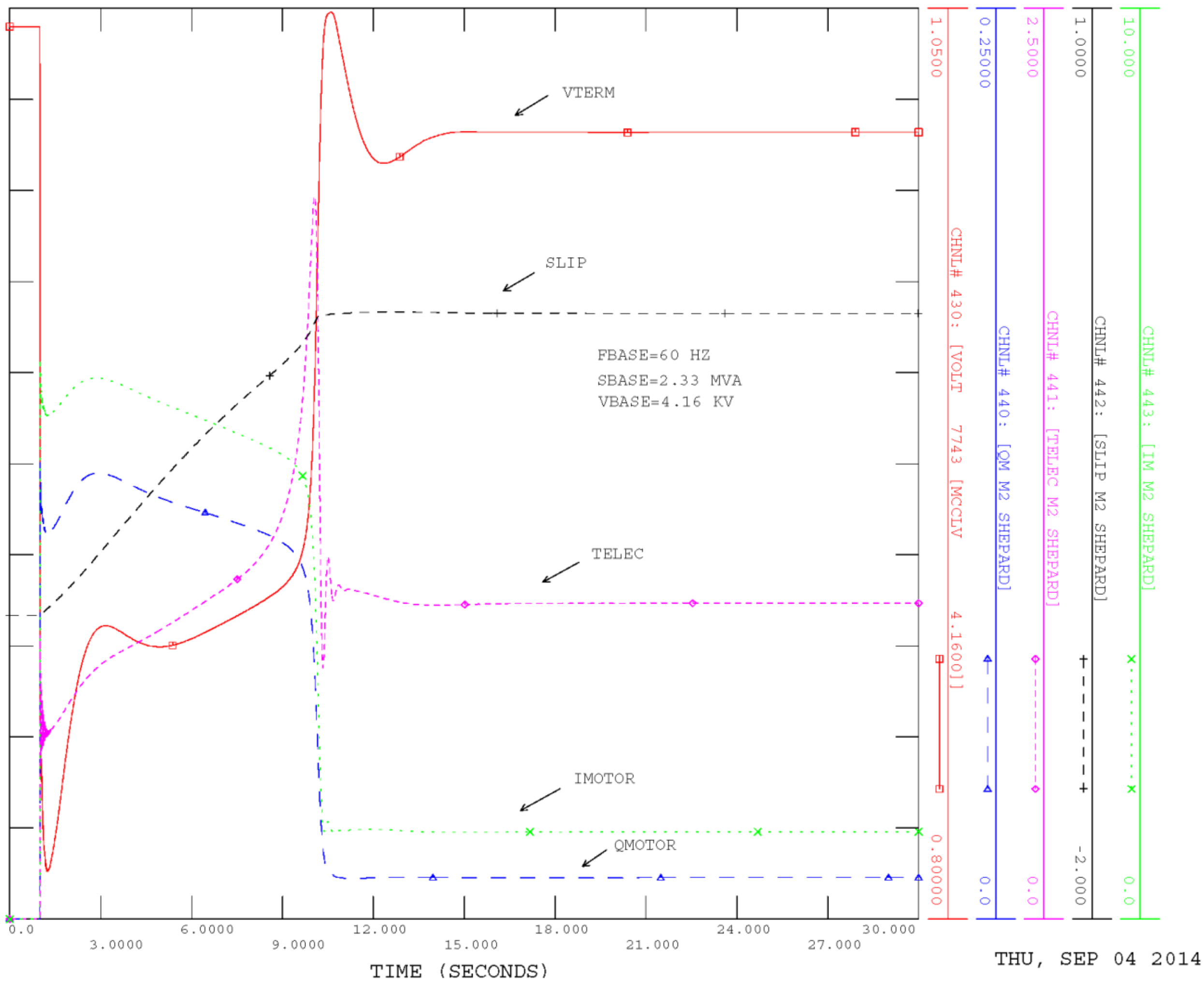

Figure 4. Motor Terminal Voltage, Reactive Power, Electric Torque, Slip and Current

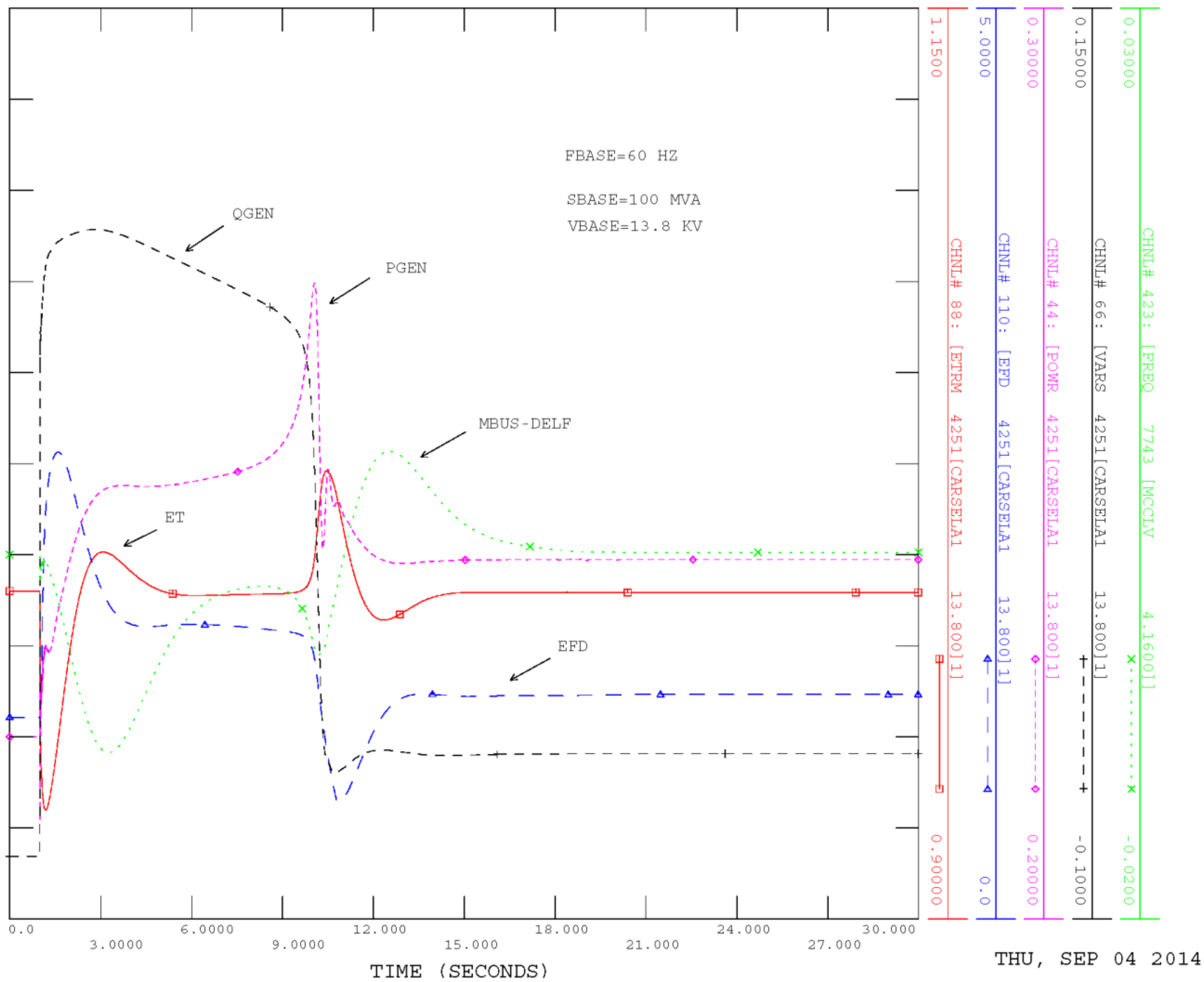

Figure 5. Blackstart Unit Terminal Voltage, Field Voltage, Reactive Power, Active Power and Frequency Deviation

Conclusions

It must be noted that restoration actions involve very unusual conditions, especially for local generation. Such factors as the ability to operate in islanded conditions with stable frequency and voltage control, availability of synchronizing equipment at key substations to permit paralleling of separate sections and the validity of assumptions on feasibility of generation to operate at unusual points of their capability are important considerations in assuring that restoration plans are viable.

Restoration actions determined from a blackstart study are not necessarily what will actually be executed should a major breakdown occur. They are based on a given set of assumptions on available transmission, amount of cold load to be picked up, destination plant(s) etc. Actual conditions could differ from these assumptions. The value of blackstart studies is in demonstrating the logic behind particular steps being taken, i.e. the cause and effect reasoning behind the choice and sequence of operator actions and the results of those actions on the power system. With this understanding the operating staff will be able to adapt to differences in the actual versus assumed conditions.

This paper has described restoration operations and the studies that should be part of a restoration planning process. In particular, it attempted to address many of the technical issues, including system dynamics and control aspects of the blackstart process.

This overview should be helpful to utility staff involved in the development of restoration plans. Development of thorough restoration plans and the testing of those plans through simulation and drills will help to minimize disruption of service to critical loads and the risk of damage to equipment following power system's partial or total blackouts.

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