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White Paper:
Recognition of Power Plant Control, Protection, and Operation in Transmission System Simulation Studies

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July 15, 2013
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and Operation in Transmission System Simulation Studies

1. Executive Summary

The NERC/FERC report *Arizona-Southern California Outages on September 8, 2011* (Joint Report) regarding the September 8, 2011 Pacific Southwest blackout identifies trips related to turbine control systems as an issue that exacerbated the consequences of the event. This white paper was developed to better inform electric power system industry participants regarding the various technical issues that relate to the tripping for the various technology types. This paper categorizes events and conditions related to tripping as follows:

a) Immediate trip of a major plant component is mandatory, regardless of conditions on the transmission system outside the plant.

b) Plant is unable, because of its inherent physical characteristics, to respond to grid conditions in the way that conventional grid control would expect.

c) Plant would be able to respond as grid control would expect, but only by taking elements of the plant into operational regimes where there is significant cumulative damage to equipment or where stability margins of in-plant controls are compromised.

d) Plant elements can continue to operate and the plant can respond as the grid expects, but only at high immediate monetary cost, out of compliance with environmental regulations, or in special control modes.

In addition to the categorization above, this paper:

- identifies two categories of trips, generator trips and turbine trips, and discusses each;
- reviews issues related to plant representation in grid power flow and dynamics studies; and
- reviews each major technology type and discusses the control issues for each.
For large steam plants, the major issues relate to overspeed protection and boiler protection. Overspeed protection is a major issue for large steam plants because of the need to handle the continued energy input when a system event occurs.

For large gas turbines, the major issues relate to overspeed control, combustion stability, and temperature control. Overspeed protection is less problematic than for steam turbines, but temperature control becomes a major issue because the turbine operates very near to the technology limits of the materials available.

Hydro plant issues relate to pressure transients, cavitation, and water levels. Hydro plants are less susceptible to unforeseen tripping than other common generator technologies.

Understanding of the ways the grid and electronically coupled generation will interact in grid disturbances is in its infancy. Nevertheless, there is good reason to anticipate that the range of protective actions and the limitations of simulation modeling that have been noted here will be found to exist with regard to new plant technologies as they do to the established ones.

2. Background

The NERC/FERC Joint Report includes Finding 21 and a Recommendation 21 as follows:

2.1. Finding 21:
“The SONGS units tripped due to their turbine control systems detecting unacceptable acceleration following operation of the SONGS separation scheme.” (Joint Report, p 105)

2.2. Recommendation 21:
“GOs and GOPs should evaluate the sensitivity of the acceleration control functions in turbine control systems to verify that transient perturbations or fault conditions in the transmission system resulting in unit acceleration will not result in unit trip without allowing time for protective devices to clear the fault on the transmission system.”

“When the SONGS separation scheme operated, turbines at SONGS began to accelerate in excess of their control system setting causing both units to trip offline. The tripping of the SONGS units in this manner raises questions about the sensitivity of the turbine control system’s settings. The units are expected to withstand severe faults on the transmission system and allow the transmission protection systems to operate without the generators tripping offline. The coordination required for this protection is not a traditional relay-to-relay coordination; rather, the setting for the acceleration function
should be coordinated with capabilities of the turbine and with the system response anticipated following operation of transmission protection systems for faults under various system conditions. The setting should also be coordinated with the system response following operation of the SONGS separation scheme. Had the turbine control system acceleration function been coordinated in this manner, the trip of the units may have been avoided.” (ibid)

2.3. WECC Response

In the WECC Response to the “Arizona-Southern California Outages on September 8, 2011” Report (Response Report) regarding activities to address the NERC/FERC recommendations, there is an O&P19 activity to address Recommendation 21 as follows:

“Evaluation of the sensitivity of acceleration control functions in turbine controls systems to system events is a complex issue. To address this issue, the Control Work Group (CWG) and WECC staff will develop a white paper to identify the issues involved and further the discussion regarding what can be done. Evaluation of system performance during the September 8, 2011 event, as well as during other events, has indicated that sometimes generators trip due to acceleration or frequency deviations and further exacerbate the effects of the event. The purpose of the white paper will be to investigate, with the generator manufacturers and owners, whether there are any steps that can be taken to identify the conditions under which generators trip and to improve models used for dynamic stability studies so the tripping can be predicted by the models.” (Response Report, pp 37, 38)

3. Introduction

Recommendation 21 is important in that it draws attention to the interface between the power plant and transmission communities in relation to the dynamics, control, and protection of the power system.

This white paper does not focus on specific issues in the coordination of any particular set of power plant and transmission elements. Rather, its objective is to remind plant and transmission communities of the breadth of issues that require joint understanding and consideration. Improvement in the joint understanding will surely lead to improved tools and techniques for ensuring that the two major parts of the power system recognize each others’ operational capabilities and limitations.
4. Power Plant Dynamics and Control Issues

4.1. Categorization of Events and Conditions

The normal presumption in the transmission communities is that generating plants will respond in accordance with the control conventions of the grid. That is, that generator real power output will respond in accordance with governing conventions (droop control), will be substantially constant, or will follow commands issued by the grid control system. Corresponding presumptions exist with regard to reactive power and voltage. Such behavior is certainly the objective of power plant operation, but it is essential for work on the grid side of the point-of-interconnection to recognize the realities of power plant operations.

It is necessary to recognize that there are many aspects of power plant control, protection, and operation that require plants to act contrary to short-term grid interests to ensure the safety and integrity of the plant and to further long-term grid interests.

It is useful to separate conditions and events in a power plant into the following categories:

a) Events and conditions where an immediate trip of a major plant component is mandatory, regardless of conditions on the transmission system outside the plant.

b) Events and conditions where the plant is unable, because of its inherent physical characteristics, to respond to grid conditions in the way that conventional grid control would expect.

c) Events and conditions where the plant would be able to respond as grid control would expect but only by taking elements of the plant into operational regimes where there is significant cumulative damage to equipment or where stability margins of in-plant controls are compromised.

d) Conditions where plant elements can continue to operate and the plant can respond as the grid expects but only at high immediate monetary cost, out of compliance with environmental regulations, or in special control modes.

The following sections of this paper identify a few important examples of the many power plant operational issues, over the range of these categories, that must be considered when assessing the consequences of transmission system events. Table 1 extends the list of examples.
The events and conditions in these categories are different for different types of power plants, but the overriding priorities in dealing with them are very similar. These overriding priorities include:

1) the safety of personnel;

2) the avoidance of immediate damage to equipment; and

3) the minimization of cumulative damage to equipment.

Action for these high priorities is almost always implemented by protective elements in the primary controls of the plant equipment. These protective elements are intended to always be in effect and independent of the actions of control room operators or external transmission grid conditions. When they are called upon, these protections act very quickly and decisively. Logging and alarming is useful for diagnosis but, particularly for category a) situations, does not give operators time to react and make corrections.

Response to cost and environmental situations (category c and d events) is less likely to be implemented in primary control or protection systems. It is more common for these issues to be managed by standing orders in the control room with operators being authorized to, or required to, act promptly on a manual time scale to bring the plant into its intended operating regime.

4.2. Generator and Power Plant Protection

The protection elements directly associated with the generator are a part, but far from the whole, of the protection system of a power plant. Thus generator protection is far from the only place where a trip of the generator can be initiated. The many other elements of the plant are monitored by their own protections, most of which are concerned with non-electrical quantities such as pressures, temperatures, or vibration. In a current-technology plant, most non-electrical protections act by operating valves or issuing status transfer signals to other control or protective elements. Few of the non-electrical protective elements in a plant issue generator trip signals directly, but many of them can initiate a sequence that will lead to a turbine or generator trip.

Note that tripping the generator and tripping the turbine are not synonymous. Some protective actions will issue trip signals to turbine and generator simultaneously, but in many cases the turbine or the generator will be tripped significantly before the other.

4.3. Initiation and Sequencing of Actions

A grid event may result in a generator trip because:

i) A fault or other unacceptable electrical condition outside the plant can only be cleared or relieved by disconnecting the generator from the transmission system.
In these situations opening of circuit breakers (main generator and/or line breakers) normally comes first and actions throughout the plant (turbine, boiler firing, etc.) follow in sequence; or

ii) The event disturbs conditions within the plant to the extent that protections not directly associated with the generator must act to protect key plant elements. In these situations the opening of the generator circuit breaker can occur as long as many seconds after the grid event has run its course.

While the timing of transmission system protection is closely related to the evolution of transmission events and mainly occurs in milliseconds, many of the critical responses in generating plants occur on time scales of seconds or even tens of seconds. Thus, the concept that protective action in a plant can be avoided by 'giving transmission protection time to act first' is often of no value. Many of the protective sequences within a plant that can limit generator output or trip it off the grid will run their course even though all transmission electrical protection functioned completely and successfully.

5. Consideration of Plant Operations in Grid Studies

Modeling of the type used in analysis of grid dynamics (load flow and stability simulations) cannot anticipate the condition of all parts of a power plant at any given time and thus cannot be relied on to determine how a plant will react to a given grid disturbance.

The reaction of a plant and the way it interacts with the grid in any proposed grid event depends on the status of a wide array of subsystems whose operating modes depend on choices made by control room operators. These choices reflect factors such as maintenance, recent history (e.g., recent startup), and problems in the plant (e.g., a leaking valve). Many, if not most, of these subsystems are not modeled in grid simulations, largely because of the impracticality of maintaining the enormous data base that would be required. Thus, there is a real risk that a simulation based on nominal modeling of a plant can be optimistic in relation to the actual behavior that would likely occur with the plant in its particular condition at a given moment. Regardless of the effort made on modeling, grid studies cannot rely solely on modeling of plant components and must always include prudent judgments. These judgments must be based on experience as to how plants actually react to grid events. Sensitivity studies examining varied scenarios of plant behavior are essential in considering grid disturbances in the close vicinity of power plants.

6. Large Steam Plant/Overspeed Protection

Overspeed of a steam turbine is a category a) event (as identified in section 4.1) and steam turbines must be very specifically protected against it. Because overspeed
protection is mandatory and built to the highest standard of dependability, overspeed failures are rare, but they are catastrophic when they do occur.

Steam turbine overspeed control cannot assume that a sudden change in electrical load has been caused by opening of the generator main circuit breaker (52G). It is entirely possible for the electrical load on the generator to drop suddenly because of a switching action at a location remote from the power plant. Overspeed protection, therefore, cannot rely on signaling of the status of circuit breakers; it must be completely autonomous and can rely only on signals that are known to the turbine protection system on an instantaneous basis at all times.

The action of the governor of a large steam turbine is not quick enough to protect against overspeed. The arrangement of turbine and boiler sections in a large power plant is such that the turbine control valves have immediate influence over only the approximately 30 percent of the total power that is developed in the high pressure (HP) turbine. The reheater section of the boiler, which is between the HP turbine exhaust and downstream turbine sections, contains a large volume of steam and entrains a significant amount of energy. As a result, the influence of the turbine control valves on the power developed in the intermediate pressure (IP) and low pressure (LP) sections of the turbine is delayed by release of the energy stored in the reheater and in the various steam volumes between the reheater and the condenser turbine. This release may have a characteristic time constant as long as several seconds.

When a sudden reduction of electrical load results in rapid acceleration of the turbine, it is essential that the intercept valves be closed quickly to prevent the energy stored in the reheater from being released into the IP and LP turbines. Common practice in North America uses quick closing of the control and intercept valves to protect the turbine from overspeed when electrical load is reduced suddenly. Within this common practice there is a broad range of individual detection, logic, and actuation schemes.

Two broad classes of control can be identified; control valves and intercept valves are closed when:

- Turbine acceleration exceeds a threshold stated in percent speed per second or equivalent units: or
- The difference between measurements of turbine and electrical power exceed a threshold stated as a fraction of rated turbine power.

Because further steam, and therefore energy, is entrained in the volumes downstream of the intercept valves and will continue to accelerate the turbine even after all valves are closed, it is essential that the closure be initiated very quickly after a loss of electrical load is detected. To ensure that the valve closure is reliably initiated soon enough to prevent overspeed reaching the level where emergency shutdown is
required, the power unbalance threshold typically needs to correspond to roughly 40 percent of turbine rating. For a turbine-generator whose inertia constant (typically) is 4.0 seconds, the corresponding acceleration threshold needs to be about $0.4/(2\times4) = 0.05$ per unit per second (180 rpm/sec).

While the first concern of the turbine control is to manage overspeed. Turbine controls can act, after overspeed is contained, to minimize the magnitude of the upset imposed on the boiler. A common practice is to reopen the intercept valves slowly after speed has been controlled and a delay has timed out. This relieves overpressure in the reheater, re-establishes steam flow in the boiler, and provides the possibility that the plant can avoid a complete shutdown. Uncorrected upset of the boiler, of course, results in complete shutdown.

In many plants, turbine overspeed protection trips the turbine but does not trip the generator. Rather the generator power decays to zero as the energy entrained in the turbine is dissipated. The generator main circuit breaker is ultimately opened by the reverse power element of the generator protection system. This practice both minimizes the overspeed by retaining whatever electrical load is available and minimizes the torsional impact on the shaft.

7. Large Gas Turbines

7.1. Overspeed Control

The control of the speed of a large gas turbine differs from that needed for steam turbines for two reasons:

- Because its internal volumes are small and air flow rates are large, there is relatively little energy stored in the gas turbine and normal governor action has good immediate influence on turbine power; and

- The compressor acts as a very effective brake.

Because a quick closure of the fuel valve produces a quick reduction of turbine power, control of overspeed after sudden load reductions is not a major issue.

With gas turbines, the practice of leaving the generator to be tripped by reverse power after the turbine has been tripped can be much less benign with regard to the grid than with steam turbines. Tripping a large gas turbine leaves the generator running as a motor driving the compressor. The power flow at the generator terminals therefore changes very quickly from full power production to consumption of as much as 30 percent of full power. Gas turbine controls can be augmented to prevent this effect and open the generator circuit breaker when the electric power flow is close to zero.
7.2. Combustion Stability

While a sudden reduction of electrical load due to overspeed may not be a category a) situation for a gas turbine, it can surely fall in category b).

Sudden loss of electrical load is a major issue in large gas turbines. To meet exhaust emissions requirements, gas turbines are operated with a very lean fuel air mixture and combustion is stable and controllable only within a narrow band of fuel-to-air ratio. Acceleration of the turbine following loss of load certainly requires reduction of fuel flow and simultaneously produces an increase in air flow. A sudden loss of electrical load thus causes a quick reduction in the fuel-to-air ratio and puts the stability of combustion at risk.

Depending on the vintage of the turbine (between the early 1990s and the present) the sudden reduction in electrical load power that a large gas turbine may be able to withstand may be small in relation to its rating. Lean blow out resulting from excessive change of the fuel-to-air ratio can appear very quickly or can evolve over as long as several seconds depending on conditions within the gas turbine. The timing of the resulting turbine and generator trip can vary accordingly. As this limitation of gas turbines has become recognized and has caused concern, combustion management features have been added to gas turbine controls to:

- Expand the allowable quick change of load by allowing compromises in aspects of turbine operation such as emissions, efficiency, or temperature; or
- Take the turbine deliberately to stable operation at minimum power or at a pre-defined mid-range power level:

Thus, as with large steam turbines, a sudden reduction of electrical load is a major issue and, for a large load reduction, the turbine must act first to ensure its own internal stability and controllability. If its control actions are successful, tripping the generator can be avoided, although a major change of turbine power may take place.

7.3. Temperature Control

Temperature issues in gas turbines lie in category b) or c), depending on duration and severity.

The temperatures in a large gas turbine are close to practical metallurgical limits. One widely used reference [1] notes that an increase in turbine inlet temperature of 100 degrees F reduces useable hot gas path life by a factor of six. Accordingly, gas turbine controls will limit or override grid-oriented governing action strongly and promptly to enforce temperature control.
Temperature control is of particular importance in grid emergencies where frequency is low because low grid frequency results in reduced air flow through the gas turbine’s compressor. Air flow falls roughly proportional to the square of compressor speed and so, to avoid overtemperature, fuel flow must be reduced roughly proportional to the square of frequency. A gas turbine running, pre-event, at maximum output must, therefore, reduce its output at exactly the time when grid control requires power plants to increase their outputs.

8. Hydro Plants

While acceleration rates of hydro and steam turbines following sudden loss of load are similar, the level to which speed can be allowed to rise is much higher for hydro machines than for steam turbines. Accordingly, the urgent tripping in response to acceleration that is essential for steam turbines is not used in the great majority of hydro plants. Rather, it has been common for hydro plants to rely on the governor for limitation of overspeed. Electrical overfrequency relays, when used, have mainly been applied as backup and set to operate at frequency levels that indicate failure of the governor.

In further contrast to steam turbines, hydro machines are essentially self sufficient. They neither depend on the range of major systems (e.g., boiler, boiler auxiliaries, and boiler controls) associated with thermal machines, nor need to be tripped because of trouble in such systems.

Because of their relative simplicity, hydro plants might be regarded as the more tolerant members of the generation community. This may be so with regard to protections acting directly on the turbine and generator, but hydro plants are no less affected than other plants by the behavior of second-level auxiliaries, as discussed in the next section.

The behavior of hydro machines may be less constrained to automatic protection and control functions, but they can be just as tightly constrained in operational terms as thermal plants. The range of factors that can constrain hydro plant operation in category c) and d) events includes:

- water levels in underground galleries
- restrictions on rapid change of tailrace flow
- cavitation and rough running of turbines
- draft tube pulsations
- limitations on use of jet deflectors and bypass valves
9. Second-Level Auxiliaries

Second-level auxiliaries are essential to the operation of all types of plants, but are rarely, if ever, recognized in the analysis of power system behavior. They range from cooling fans in the main electronic systems to hydraulic pressurizing pumps in mechanical systems. They range in size from fractional horsepower to tens of kilowatts. These second-level auxiliaries such as cooling fans seldom have protection that can send a trip signal directly to the turbine or generator but must, nevertheless, be considered when reviewing the security of a plant. A brief disturbance of voltage or frequency during normal operation of the power system should not stop these second-level auxiliaries. However, an otherwise routine disturbance occurring in the close wake of a prior event or a prolonged period of low voltage or frequency can reduce their performance to the extent that the primary systems that they support are affected. As an example, if the cooling fans of an electronic exciter run slowly or stall the exciter will eventually be tripped, either because of high temperature or by detecting that the fans are not running. The generator is then tripped by loss of excitation even though the exciter bridge may have been within its own protection limits and otherwise able to support the generator.

10. Converter Connected Generation (Wind and solar plants)

In contrast to the industry’s many thousands of plant-years of experience with the behavior of plants based on direct-connected synchronous generators, the industry is in the very early stages of its experience with electronically-connected generation.

Where electronic converters are supplied by mechanical sources (mainly, but not exclusively wind turbines), issues such as overspeed and security of auxiliaries that are fundamental in direct-connected plants will very likely continue to be of concern. Where the energy source is purely electric, as with batteries and photocells, the relationship of protections on the supply side of the converters to grid conditions is very much an emerging subject. Experience with DC transmission and static volt-ampere reactive devices gives some limited guidance regarding the behavior of electronic converters but is not informative regarding the relationships between converters and their energy sources (e.g., generators, batteries, photovoltaic panels).

It is perhaps reasonable to expect that converter connected plants will be less sensitive than ‘conventional’ plants to low voltage or frequency deviations, but more sensitive to, and more likely to trip in, high voltage situations.

Converter systems in wind and solar plants will be dependent on second-level auxiliaries as are the electronic systems of other plants.
11. Conclusions and Recommendations

The recommendation of the FERC/NERC Joint Report regarding the tripping of turbines because of rapid acceleration is important, first in its reference to the specific issue of protection coordination, and second, in its inferred concern that improvements are needed in the way protection systems are represented in grid simulation studies.

Individual elements such as overspeed protection can certainly be incorporated into the grid simulation programs used by WECC. WECC cautions; however, that it will not be practical for the individual details of such elements to be described explicitly for each of the many power plants considered in grid-wide simulations.

Regardless of the introduction of new modeling into the grid simulation programs, it will continue to be necessary to recognize that:

a) power plants will always act to protect themselves and that protection of a plant may require the generator to be tripped even though grid conditions close to the plant do not.

b) non-electrical in-plant protections cover so many diverse physical situations that ‘coordination’ with transmission protection in the electrical relaying sense is impractical.

c) the responsibility for the design and correct functioning of all the protection in a plant lies with the plant owner.

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