# PROTECTION CONSIDERATIONS FOR BLACK START GENERATORS


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## I. INTRODUCTION

Application of sound relaying principles helps prevent unwanted tripping during black starts. An unwanted trip during a black start is extremely detrimental since the utility is attempting to reconnect its high voltage grid and restore service throughout its operating region.

A **black start** is *the process of restoring a power station to operation without relying on external power sources*. Normally, the station generators provide the electric power used within the plant, also called station service power. If a shutdown of all the generators occurs, the high-voltage grid provides station service power through the transmission lines. This off-site power source is not available during a wide-area outage. Therefore, a black start is required in the absence of grid power. Generating plants using steam turbines require station service power up to ten percent of their total load capacity (to bring on-line: boiler-feed water pumps, boiler-forced draft combustion air blowers, and fuel preparation equipment, for example). It is uneconomical to provide such a large standby capacity at each station, so the electrical transmission network only provides black start power from specific stations. Hydroelectric power plants are often designated as the black start sources to restore network interconnections since these stations need very little initial power to start and can put a large block of power on line very quickly to allow start-up of fossil fueled and nuclear stations.

Careful detailed analysis is required to properly apply generator protection at stations with black start capability. Generator relay current inputs are subjected to high levels of dc offset and harmonic current due to energizing transformers during a black start. Proper selection of current transformers for the generator differential protection is necessary to avoid a mismatch. Both the system side and neutral side sets of current transformers should have the same saturation voltage characteristics because if there is a large dc offset present the current transformers can saturate with restraint current significantly less than two times the nominal relay current.

The case of a generator differential protection misoperation during a black start at a large hydro station is examined in detail to illustrate what steps to take to prevent these types of nuisance trips without sacrificing relay sensitivity. An unwanted trip occurred because of the particular differential-protection operating characteristic. One solution presented monitors the harmonic content of the relay current to de-sensitize the differential protection momentarily while the transformer draws *heavy inrush* current. Also discussed is the use of a second generator differential element in tandem with the first to minimize the chance of an unwanted trip from occurring during a black start.

## II. GENERATOR DIFFERENTIAL TRIP DURING DEAD BUS TEST

This event occurred during the fall of 2008. The hydroelectric generating company had two windings on the low side of each of the step-up transformers at this plant. Two generators were connected to each low side winding. The test described below was not a normal practice.

### A. Dead Bus Test Procedure

Normally, the step-up transformer is energized from the 230 kV transmission grid (Figure 1). This particular test was performed to prove that the generating company could pick up the station service transformer for essential loads—such as the sluice gate spillway supply—should a system blackout occur. This is considered a dead bus operation. The transmission company opened the step-up transformer high-side breaker and the generators continued to turn at speed with no load. The plant was attempting to only pick up station service; however, the step-up bank had to be picked up as well since the plant cannot remotely isolate the step-up transformer.

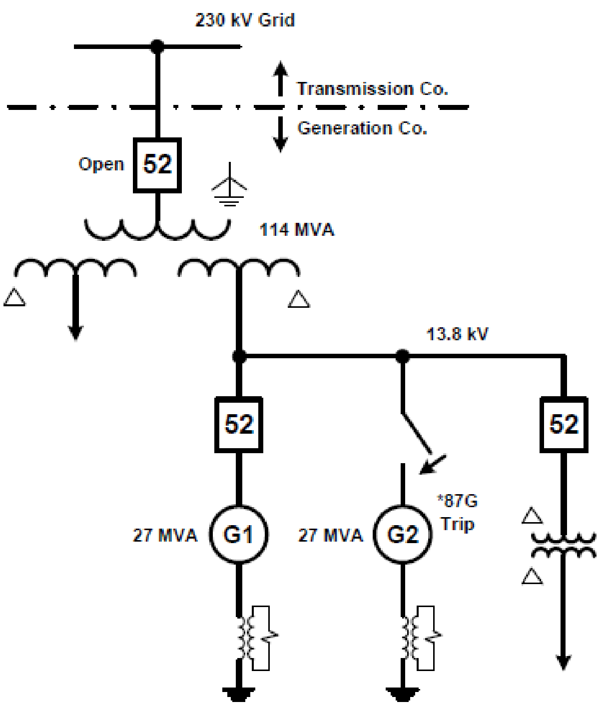



**FIGURE 1: Hydroelectric power plant single-line diagram**

### B. Protection

There are two multifunction numerical generator protection relays per generator, Main I and Main II. Each relay is provided by a separate vendor. Main I generator protection relay operated on differential during transformer energization.

### C. CT Saturation

Review of the oscillography captured by the relay for this event revealed that there was *significant* mismatch present in A-Phase and C-Phase CT secondary currents from both the neutral ($I_{abc}$) and system ($I_{ABC}$) sides of the generator windings. The mismatch was due to the different voltage class ratings for the neutral- and system-side CTs. The neutral-side CTs are rated 10L300 while the system-side CTs are rated C400. Therefore, the neutral-side CTs have a saturation voltage roughly equal to 300 volts while the system-side CTs have a saturation voltage roughly equal to 400 volts.

Figure 2 and Figure 3 show the individual differential currents for A-Phase and C-Phase. If the 9th positive peak in Figure 2 is examined, it can be seen that $I_a$ is more saturated in comparison to $I_A$.

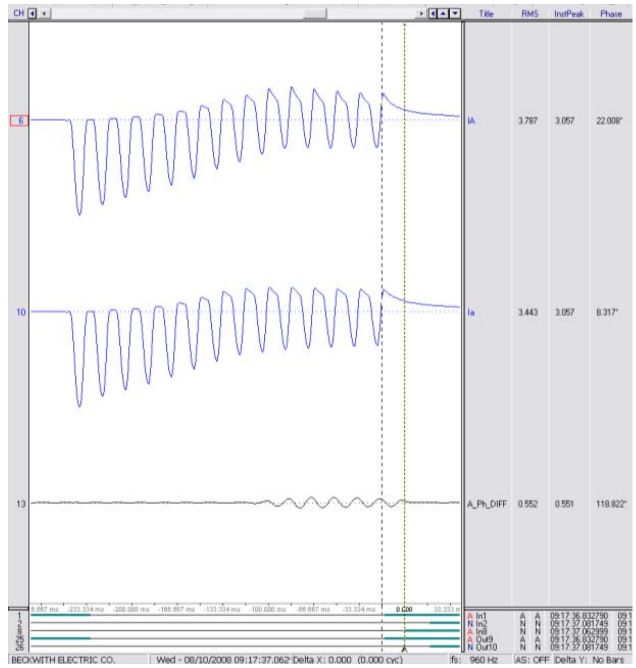



**FIGURE 2: A-phase differential current**

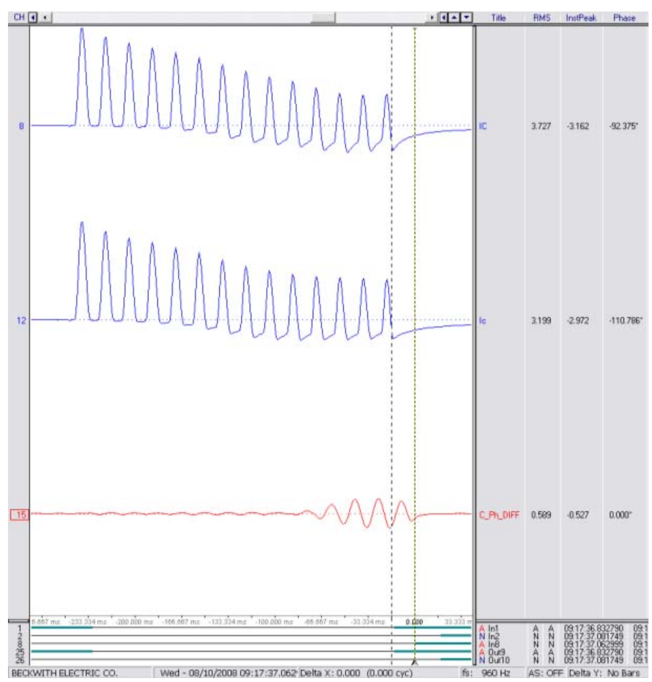



**FIGURE 3: C-phase differential current**

Figure 4 is the same as Figure 3, but all three signals (IC, Ic, C_Ph_DIFF) are superimposed onto the same channel.

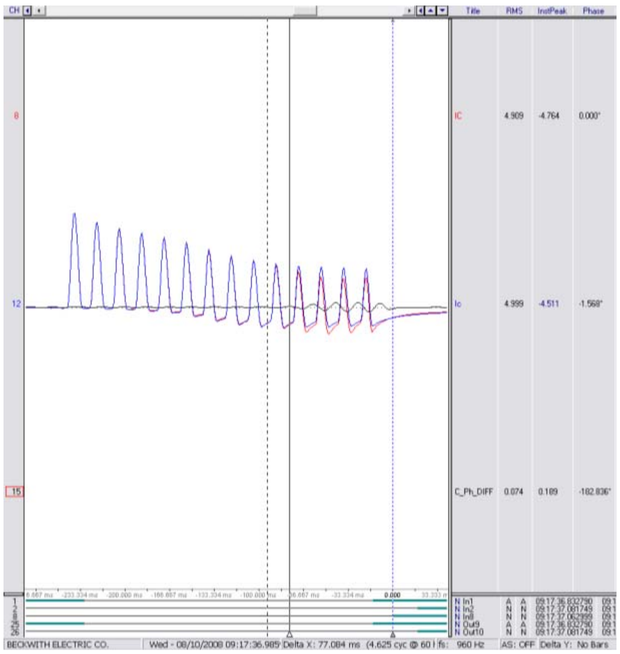


**FIGURE 4: C-phase differential current (superimposed)**

Figure 5 shows the CT excitation characteristics for the A-Phase CTs on both the neutral- and system-side of the generator windings. Review of the two characteristics reveal there is over 500 milliamps difference at 400 volts and higher. As has been noted, there were significant amounts of both dc and 2nd harmonic content in the current due to energizing the transformers; dc current quickly saturated the CT causing it to draw more excitation current.

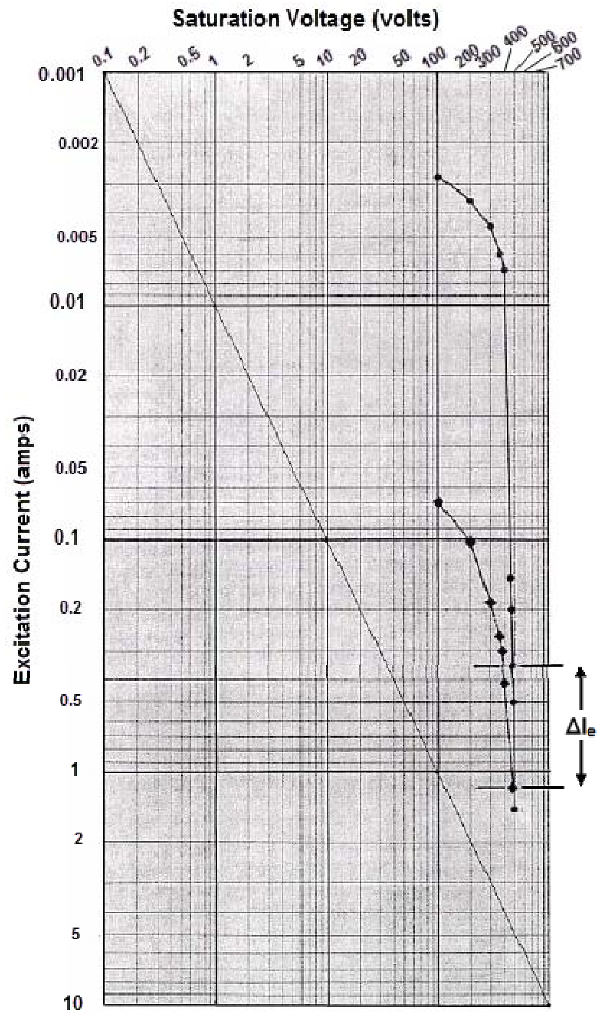



**FIGURE 5: A-phase CT excitation characteristics**

**D. Generator differential misoperation**

Main II numerical generator differential protection has a CT saturation detection algorithm to improve security. If there is dc offset present (such as the case for transformer energization during a black start), CTs can saturate with restraint current significantly less than two times nominal. Main II numerical generator differential protection automatically multiples the slope by four times (Figure 6) if the total RMS differential current is greater than the fundamental differential current. The total RMS differential current calculated by the relay contains dc and the 1st through 5th harmonic components.

Figure 6 illustrates the generator differential protection characteristics. The operating points for A-Phase and C-Phase appear to the far right of the characteristic. Main II numerical generator differential protection did not operate due to the CT saturation algorithm; that is, there was high dc current present and the protection automatically multiplied the slope by four times.

The vendor for Main I numerical generator protection recommended either increasing the slope to 30 percent or enabling harmonic blocking. A slope of 30 percent is permanent and results in much less sensitivity during internal faults. Harmonic blocking could result in no operation or delayed operation during CT saturation. Main II numerical generator differential protection automatically multiplies the slope by four times as illustrated in Figure 6, and the slope returns to normal eight cycles after dc and harmonic content in the differential current subsides.

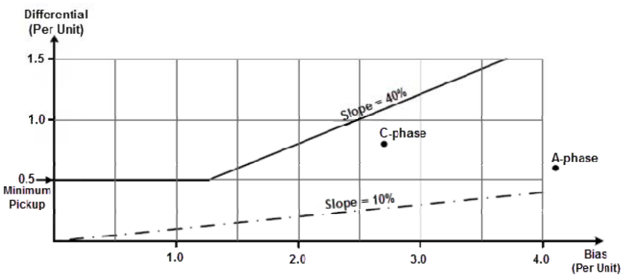



**FIGURE 6: Generator differential protection characteristics**

**E. Dual differential elements operating in tandem**

Another solution is to use two differential elements in parallel. The first differential element has a lower slope and provides maximum sensitivity. The second differential element has a higher slope and as a result is more secure. The first element is inhibited by an external input during black starts while the second element is free running. Figure 7 is a logical diagram for the dual 87 scheme while Figure 8 shows how this can be implemented via relay settings.

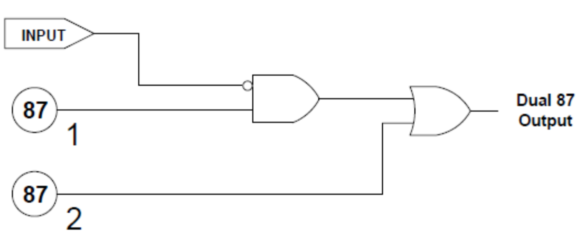



**FIGURE 7: Dual 87 logic diagram**

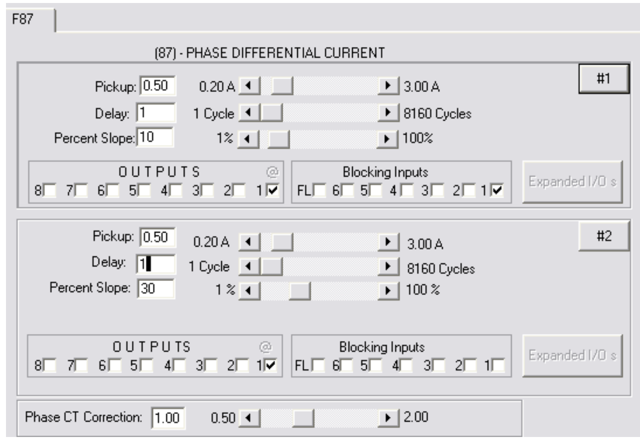



**FIGURE 8: Dual 97 relay settings**

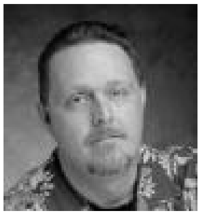
**III. CONCLUSIONS**

Application of sound relaying principles helps prevent unwanted tripping during black starts. An unwanted trip during a black start is extremely detrimental since the utility is attempting to reconnect its high voltage grid and restore service throughout its operating region.

Careful detailed analysis is required to properly apply generator protection at stations with black start capability. Generator relay current inputs are subjected to high levels of dc offset and harmonic current due to energizing transformers during a black start. The current transformers used for generator differential protection ideally should be identical to avoid any mismatch. Both the system side and neutral side sets of current transformers should at least have the same saturation voltage characteristics because if there is a large dc offset present, the current transformers can saturate with restraint current significantly less than two times the nominal relay current.

Some numerical generator protection relays have the ability to detect that transformer automatic energization is in-progress and take steps to prevent unwanted operation —such as momentarily de-sensitizing the differential protection. Dual differential elements operating in tandem provides security during inrush conditions and reliability during internal faults.

## IV. BIOGRAPHY



**Steve Turner** is a Senior Applications Engineer at Beckwith Electric Company, Inc. His previous experience includes working as an application engineer with GEC Alstom for five years, primarily focusing on transmission line protection in the United States. He also was an application engineer in the international market for SEL, Inc. again focusing on transmission-line protection applications. Steve wrote the protection-related sections of the instruction manual for SEL line protection relays as well as application guides on various topics such as transformer differential protection and out-of-step blocking during power swings. Steve also worked for Progress Energy in North Carolina, where he developed a patent for double-ended fault location on transmission lines and was in charge of all maintenance standards in the transmission department for protective relaying.

Steve has both a BSEE and MSEE from Virginia Tech University. He has presented at numerous conferences including Georgia Tech Protective Relay Conference, Western Protective Relay Conference and Doble User Groups, as well as various international conferences. Steve is also a senior member of the IEEE.