AVOID GENERATOR SYSTEM DAMAGE DUE TO A SLOW SYNCHRONIZING BREAKER - PART I

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Generators, transformers, and associated equipment can be damaged if a breaker closes and connects two systems while they are not synchronous (out-of-step). If the breaker physically closes slower than anticipated, the systems move outside the designated synchronous conditions before the breaker closes. Once the breaker close coil is energized, the close process cannot be reversed. Because of documented slow breaker closing conditions, a secure, reliable, cost-effective solution was developed to avoid future problems.

Applying this new innovative solution to detect the slow breaker allows time for breaker isolation and avoids unnecessary system disturbances and damage. In addition, this solution allows for a test mode for additional security.

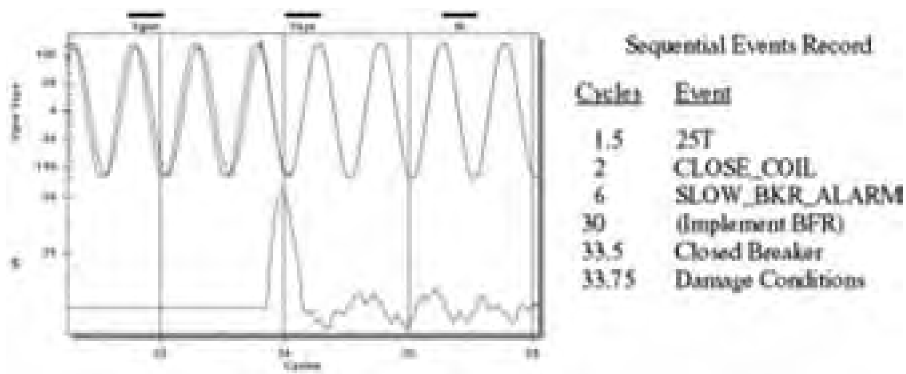

Figure 1: Slow Synchronizing Breaker Operation, Oscillographic Display and SER

Overview of Results

Simulations, laboratory tests, and field operations verified that a secure and reliable breaker failure scheme to isolate a slow synchronizing breaker was possible. Using various power system measurements such as current, voltage, angle, voltage difference, and slip frequency gave the scheme the desired security and reliability.

THE PROBLEM

Connecting a synchronous generator to a large interconnected power system is a dynamic process, requiring the coordinated operation of many components and systems (i.e., electrical, mechanical, and often human). The goal is to connect the spinning generator to the system smoothly, i.e., without causing any significant bumps, surges, or power swings, by closing the breaker when the generator matches the system in voltage magnitude, phase angle, and frequency. Except for the rare occasion when the match happens to be exact, some amount of power will flow into or out of the generator to force it into step. If that synchronizing power is excessive, severe damage to the generator and associated equipment can result.

Over the more than 100-year history of alternating current electricity in the world, various schemes have been developed to make the synchronizing process as smooth and reliable as possible. These techniques are as simple as manually adjusting a throttle while watching for a light to go dark before turning the control switch to close the generator breaker. Or, they are as high-tech as a completely automated system under direct control of a computer.

To monitor the voltage angle and frequency across the open breaker, the operator may use a synchroscope. The synchroscope appears as a clock with a sweep second hand and is connected so it will rotate clockwise when the generator is faster than the system (Figure 2a). Most synchronizing schemes begin with the turbine-generator running slightly faster than system frequency, with field applied, and voltages matched (Figure 2b). This ensures that the generator will pick up a minimum amount of load to prevent tripping on reverse power. At the 12 o'clock position, the generator voltage angle exactly matches that of the system. The smaller the frequency difference, or slip frequency, between the generator and system voltage, the slower the hand moves.

When conditions are right, just before the synchroscope reaches 12 o'clock, the breaker is given a signal to close (Figure 2a) so the breaker contacts will meet when the voltage across them is as close to zero as possible (Figure 2b). In the vast majority of synchronizing events, this works very well. All synchronizing schemes, whether manual or automated, rely on the circuit breaker closing at a consistent speed to complete this final step successfully.

Unfortunately, as experience has shown, circuit breakers do not always close as quickly as expected. It is the nature of virtually all types of breaker operating mechanisms that, once the signal to close is given, the breaker must go completely closed before it can be tripped.

Reversing a partially closed breaker could result in violent failures. If any part of the mechanism (i.e., coil, valve, solenoid, latch, lever, etc.) hangs up from depressed control voltage, corrosion, or degraded lubrication, the closing operation is slowed down. When the closing operation is slowed down and the break-

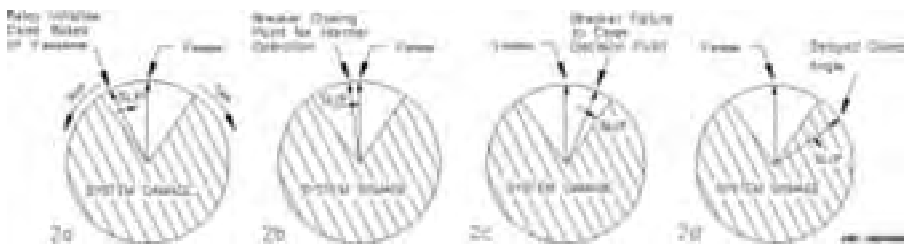

Figure 2: Generator and System Voltage Synchroscope Representation

er finally does close, it may close at the worst possible time, if it connects a generator out-of-step (Figure 2d).

ACTUAL OCCURRENCES

Wisconsin Electric (WE) became aware of the problem of slow synchronizing breakers about five years ago at the Pleasant Prairie Power Plant (PPPP or P4). Refer to Figure 3 for the P4 single line diagram. P4, the largest generating plant in Wisconsin, has two identical 580 MW net units, fueled by western subbituminous low-sulfur coal. The generators are 24 kV, unit-connected through step-up transformers to the 345 kV switchyard. Both units use automatic synchronizing relays. The entire unit startup sequence is initiated by either operator action or a plant computer.

On July 14, 1992, the Unit 1 generator (G1) at P4 was being brought back online following a brief unplanned outage, when it experienced out-of-step synchronizing caused by delayed closing of the 345 kV generator breaker (610). Less than two seconds after the breaker closed, the Unit 1 turbine was tripped by high vibration from shaft torsional oscillations caused by the shock of the disturbance. The generator breaker (610) tripped about 31 seconds later by reverse power. The out-of-step closure of Unit 1 caused the Unit 2 turbine to trip almost immediately due to large power swings between the two generators and the system. The Unit 2 generator breaker (640) subsequently tripped by reverse power about 20 seconds after the out-of-step closure of Unit 1.

The generator breaker (610) on P4 Unit 1 is a 345 kV live-tank sulfur hexafluoride (SF6) design with a pneumatic operating mechanism. Following the incident, it was learned that this particular model of breaker had experienced similar delayed closures at other utilities around the country. When the breaker closed following extended periods of inactivity, the operating mechanism pilot valve would stick. Although users of this breaker were not broadly informed of the problem, a modification to the closing mechanism was available from the manufacturer. The modification involved replacing the pilot valve with one less susceptible to sticking and a modification to the main valve piston. This modification has since been made to the P4 Unit 1 breaker (610), the only one of its type in use as a generator breaker on the WE system. Other

WE installations of this breaker are on transmission lines where synchronized closings do not involve a slip frequency. The Unit 2 breaker is a dead-tank SF6 design from a different manufacturer and presumably does not have the same problem.

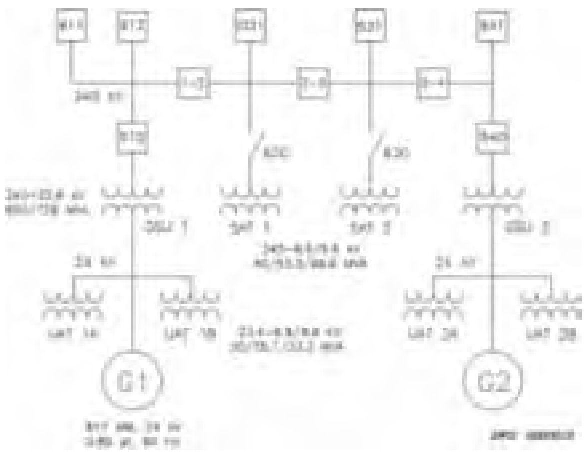

Figure 3: Single Line Diagram of Pleasant Prairie Power Plant (P4) Wisconsin Electric Power Company

WE also learned that delayed closing is not unique to this particular breaker. A sampling of trouble reports from Edison Electric Institute (EEI) and Institute of Nuclear Plant Operators (INPO) from the

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previous 10 years revealed at least 15 incidents of generator out-of-step synchronization due to delayed closings, involving a wide variety of breaker ages, manufacturers, types of operating mechanisms, and voltage levels. The problem exists whether manual or automatic synchronizing is used and with or without synchro-check relays.

A recent IEEE survey of the industry reported that 6 of the 32 respondents experienced misoperations of their synchronizing scheme. The survey stated, “There were three instances of late breaker closing reported with no apparent damage. A slow breaker was responsible for one of these cases. Another was due to a setting error on a permissive device. One was the result of a mismatch by the automatic control features.” This information could overlap the EEI and INPO reports because sources were not indicated.

These actual occurrences had different reasons for the slow breaker close operation. Poor maintenance, faulty breakers, faulty synchronizers, and failed auxiliary equipment were all reasons for the various misoperations. The consequences of the misoperations ranged from unit outage time to the explosion of the breaker.

The knowledge that the P4 occurrence was not an isolated incident led WE to conclude that the breaker manufacturer’s modification is not a permanent fix and that other turbine-generators could be exposed to possible damage from delayed breaker closings. A damaged or destroyed generator, step-up transformer, or generator breaker could result in many months of down-time plus the expense of the repair and replacement energy and possible injury to personnel. Thus, WE sought a means of preventing or alleviating damage from slow breaker closings.

COST OF THE PROBLEM

Equipment Damage

The actual closing time or relative angle could not be precisely determined in the P4 case, but indications are that the Unit 1 generator breaker took about three seconds to close and the machine was more than 90 degrees ahead of the system when the breaker closed. Though no detectable damage was found to either generator or their step-up transformers, it is almost certain that some loss of life was sustained from shaft torsional oscillations and shifting of windings. This conclusion was based, in part, on a May 1976 analysis conducted by personnel from Westinghouse Electric Corp. and Consumers Power Co. following an out-of-step closure on a 955 MVA generator. That analysis concluded that the turbine-generator could have experienced as much as 5% loss-of-life during a worst-case 120° out-of-step synchronization. Repair or replacement costs of a damaged generator or step-up transformer could have reached \$3 to \$5 million.

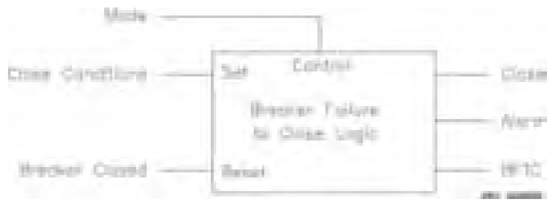

Figure 4: BFTC Scheme Block Diagram

Equipment Unavailability

Out-of-step breaker closures are very expensive, even if physical damage is undetectable. In the case of P4, Unit 2 was forced out of service for about five hours. Unit 1 was returned to service two days later, following extensive testing and analysis of the operation. The cost to WE was estimated at about \$270,000, with most of the cost due to replacement power, since P4 is WE’s most economical plant. The time to repair or replace a damaged generator or step-up transformer could have reached six months to one year. The cost of providing power from a more expensive generator or purchasing the power from another source could have reached \$25 million.

A SOLUTION TO THE PROBLEM

Wisconsin Electric applies breaker

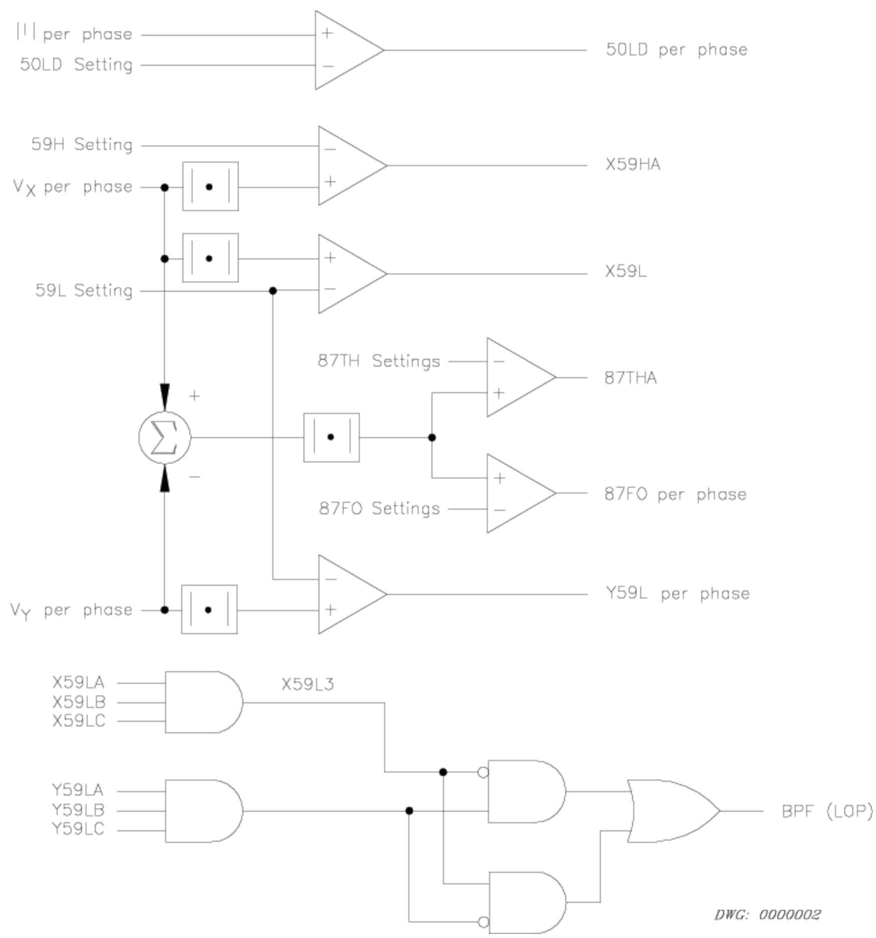

Figure 5: Power System Measurements

failure-to-trip protection, inadvertent closing protection, and pole flashover protection on generator breakers at all major generating stations. These schemes will not detect, nor protect from, breakers closing out of synchronism. Neither automatic synchronizing nor synchro-check relays prevent slow breaker closings, since they stop working once a close signal is given to the breaker.

To be effective, breaker failure-to-close (BFTC) protection must allow sufficient time for the breaker to close without allowing the generator to get too far out of step with the system. If a close does not occur before the generator gets too far out of step, the protection must trip adjacent breakers to isolate the slow breaker from the rest of the power system, similar to a breaker failure-to-trip scheme. Then, when the breaker finally does close, it will merely connect the generator to a deenergized bus and no damage will occur. The logic should also allow monitored test closing of the breaker, providing an alarm if the closing speed was inadequate, so the problem can be corrected before attempting actual synchronization. Experience has shown that exercising a slow breaker can often improve its closing speed. Of course, a BFTC scheme carries the risk of operating falsely to cause unnecessary bus clearing.

However, the consequences of such over-tripping are much less severe than the possible damage from an out-of-step synchronization. A successful test close prior to attempting synchronization will greatly enhance security, a primary goal of the scheme.

WE considered a scheme developed by another utility that uses a series of timers, indicating lights, and switches to count the time following a close signal. A set time is calculated predetermined to be safe based on normal slip frequency and breaker operation times. If the breaker does not close (as indicated by the breaker auxiliary contacts) before the set time, the breaker failure lockout relay is tripped. This scheme relies on timing once the close signal is initiated. Actual voltage and phase angle difference across the open breaker are not measured. If the generator or the system frequency or voltage changes significantly, the scheme could fail to protect the generator or needlessly cause a bus clearing. The time setting must accommodate variations in personal habits among human operators and differences between human operators and automatic synchronizers relating to preferred slip frequency and advance closing angle.

WE seriously considered adapting such a scheme, but did not proceed because of its complexity.

WE has avoided further BFTC incidents by exercising the generator breakers, wherever possible, prior to attempting to synchronize. Some of the plants, however, do not have the ability to isolate the generator breaker for exercising. And even when the breakers are exercised, WE still cannot be absolutely certain that the closing speed is adequate because the breaker closing time is not measured. Still concerned, WE chose to pursue new concepts to resolve the problem.

Conceptual Overview

A BFTC scheme should monitor the actual phase angle and voltage differences across a generator breaker before and after a close is given, and operate if either quantity is outside an acceptable window before the breaker closes. Since the real criteria for protecting against out-of-step closure are the relative voltage and angle of the generator with respect to the system, knowing the nominal breaker closing time and normal slip frequency is not necessary. Reliance on breaker auxiliary contacts to represent breaker status is also not necessary. Breaker closure could be definitely confirmed by the absence of a voltage difference and the presence of current through the breaker.

Figure 2 is a series of figures representing a synchroscope. VGENERATOR rotates in a clockwise direction with respect to the reference VSYSTEM and the speed of which is referred to as generator "slip". Because the circuit breaker takes a finite time to be physically closed after close initiation, the device or operator initiating the close must anticipate the close condition.

Depending on the generator slip and the circuit breaker close time, an example of where the close initiation should occur is shown in Figure 2a. The breaker should be physically closed by the time VGENERATOR has slipped to Figure 2b. If the breaker does not close, VGENERATOR continues to rotate (slip) in a clockwise direction. If VGENERATOR slips to Figure 2d and the breaker physically closes, system damage will occur. The system damage angle is determined for each individual case based on an acceptable closing angle for the system. In order to avoid this damage, a decision is made at the point shown in Figure 2c allowing enough time to clear the bus before the breaker closes.

In addition to the above requirements, the implementation at WE included additional security logic and the ability to gen-

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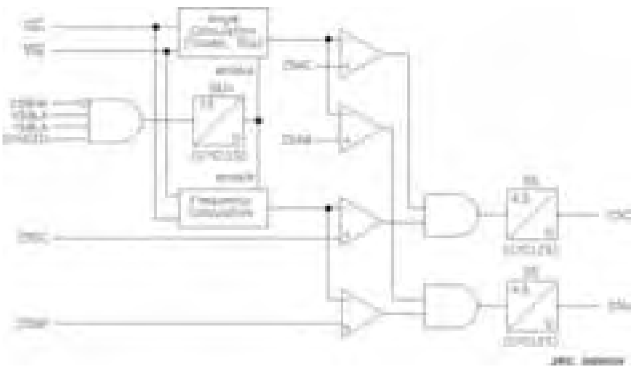

Figure 6: Synchronous Conditions Verification

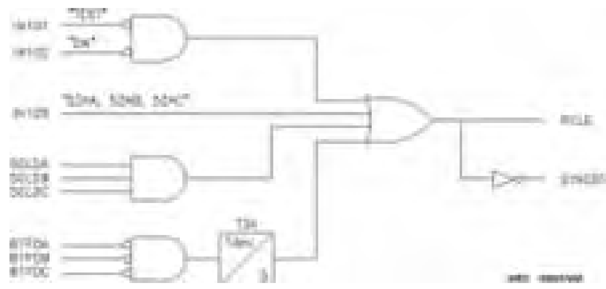

Figure 7: Breaker Closed (RCLS), Scheme Reset Logic

short lines protection

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erate the anticipated close condition. A block diagram of the scheme is shown in Figure 4. The inputs include the mode of the logic, the close conditions, and the breaker status to determine the three outputs. The outputs energize the close coil, energize an alarm, and/or energize a breaker failure lockout relay.

AC Measurements

The relay must make certain power system measurements to implement the logic. Figure 5 shows the comparisons of power system measurements and threshold settings. Each output shown is used in the control logic. Power system voltages and currents are used for the comparisons. Two sets of three-phase voltages and a set of three-phase currents are measured and compared according to Figure 5. For example, when one of the current inputs exceeds the 50LD threshold setting, the corresponding output asserts (50LDA, 50LDB, or 50LDC). A subset of the currents and voltages may be used without severely affecting the scheme's functionality.

Synchronous Conditions

The logic in Figure 6 shows the measurements of the two voltage sources (VAX and VAY) for determining the proper time for circuit breaker close initiation which is the output, 25C (synchronous close). The 25M output is a second synchronous measurement, but is used in the control scheme to indicate that generator slip is greater than some threshold.

Frequency

The frequency of the generator A-phase voltage with respect to the system A-phase voltage must have a slip less than a predetermined setting (25SC).

Angle

The angle of the generator A-phase voltage with respect to the system A-phase voltage must be less than a predetermined setting (25AC). The angle calculation takes into account the slip frequency and nominal circuit breaker close time (Tclose) to indicate when 25C should assert.

This makes the 25C condition true at a time when the system is actually not synchronous, but after the time-delay of the circuit breaker closing time the two systems will be synchronous.

Enable Conditions

Both the angle and slip calculations require certain enable conditions be true. These enable conditions provide scheme security, including: sufficient generator A-phase voltage (X59L), sufficient system A-phase voltage (Y59L), generator A-phase voltage is below overvoltage threshold X59H, and any other programmable condition called SYNCEN. In this case, the programmable SYNCEN input verifies the scheme is enabled and the circuit breaker is open.

Open or Closed Breaker

Figure 7 presents the logic that indicates when the scheme is enabled and the circuit breaker is closed. The output of this logic is the SYNCEN and RCLS conditions which are inputs to the other logic shown in Figure 6 and Figure 8. Two control inputs put the scheme in one of three modes: OFF (neither IN101 nor IN102 inputs are asserted), ON, or TEST. The scheme is enabled only when it is in the "ON" or "TEST" mode and the circuit breaker is open.

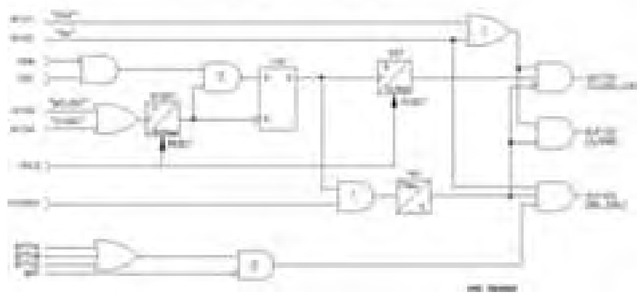

Figure 8: Breaker Failure-To-Close Logic

An open circuit breaker is indicated by three conditions: one or more of the three current detectors are dropped out, the circuit breaker status input is not asserted, and the voltage difference across the circuit breaker has not been zero for a specified amount of time (T3pu).

These conditions assert the SYNCEN output.

The scheme is reset and disabled when the RCLS output is asserted. RCLS asserts when the circuit breaker is closed or the scheme is in the "OFF" mode. The circuit breaker is considered closed when all three current detectors pick up, the circuit breaker status input asserts, or the voltage difference across the circuit breaker has been zero for a specified amount of time (T3pu).

See in the next issue of Electricity Today for Part II