

Avoid Generator and System Damage Due to a Slow Synchronizing Breaker

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INTRODUCTION

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.

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.

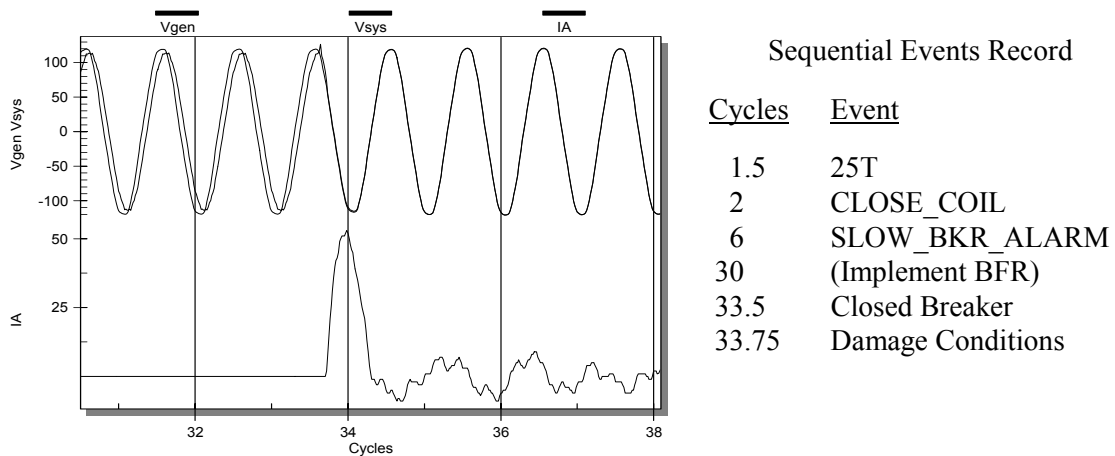


Figure 1: Slow Synchronizing Breaker Operation, Oscillographic Display and SER

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

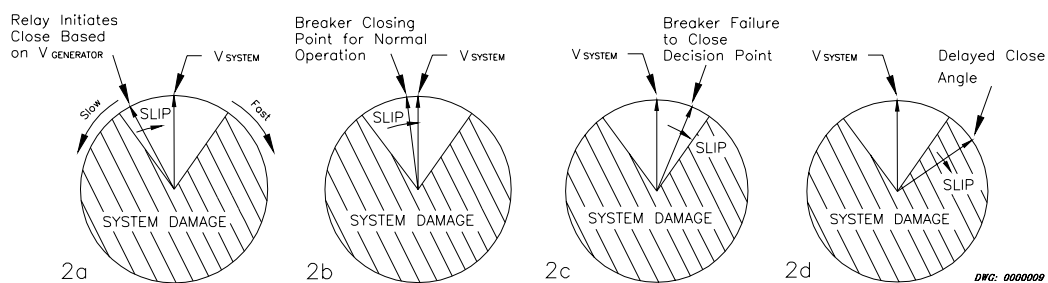
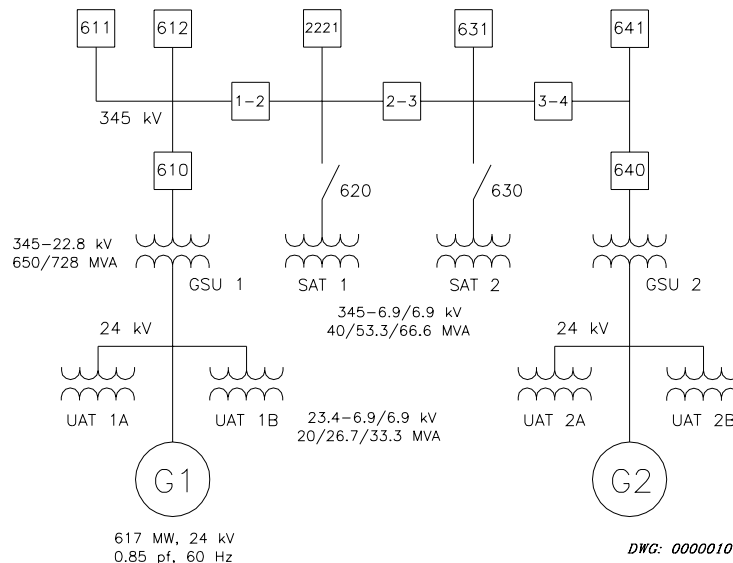


Figure 2: Generator and System Voltage Synchroscope Representation

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 sub-bituminous 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.



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

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.

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 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 [1] 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° 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. [2] 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.

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 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 difference 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. $V_{\text{GENERATOR}}$ rotates in a clockwise direction with respect to the reference V_{SYSTEM} 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 $V_{\text{GENERATOR}}$ has slipped to Figure 2b. If the breaker does not close, $V_{\text{GENERATOR}}$ continues to rotate (slip) in a clockwise direction. If $V_{\text{GENERATOR}}$ 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 generate 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.

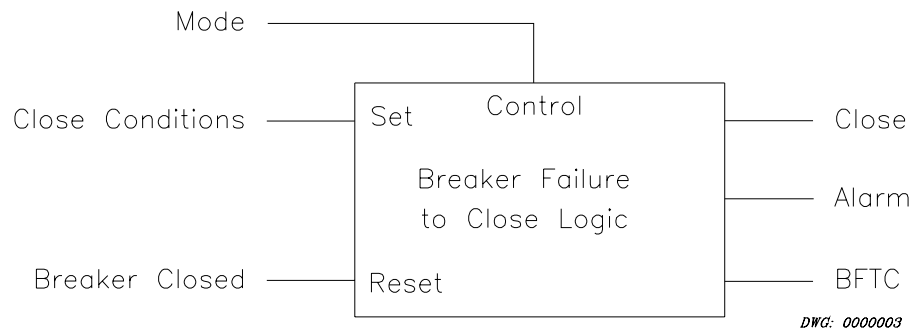


Figure 4: BFTC Scheme Block Diagram

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.

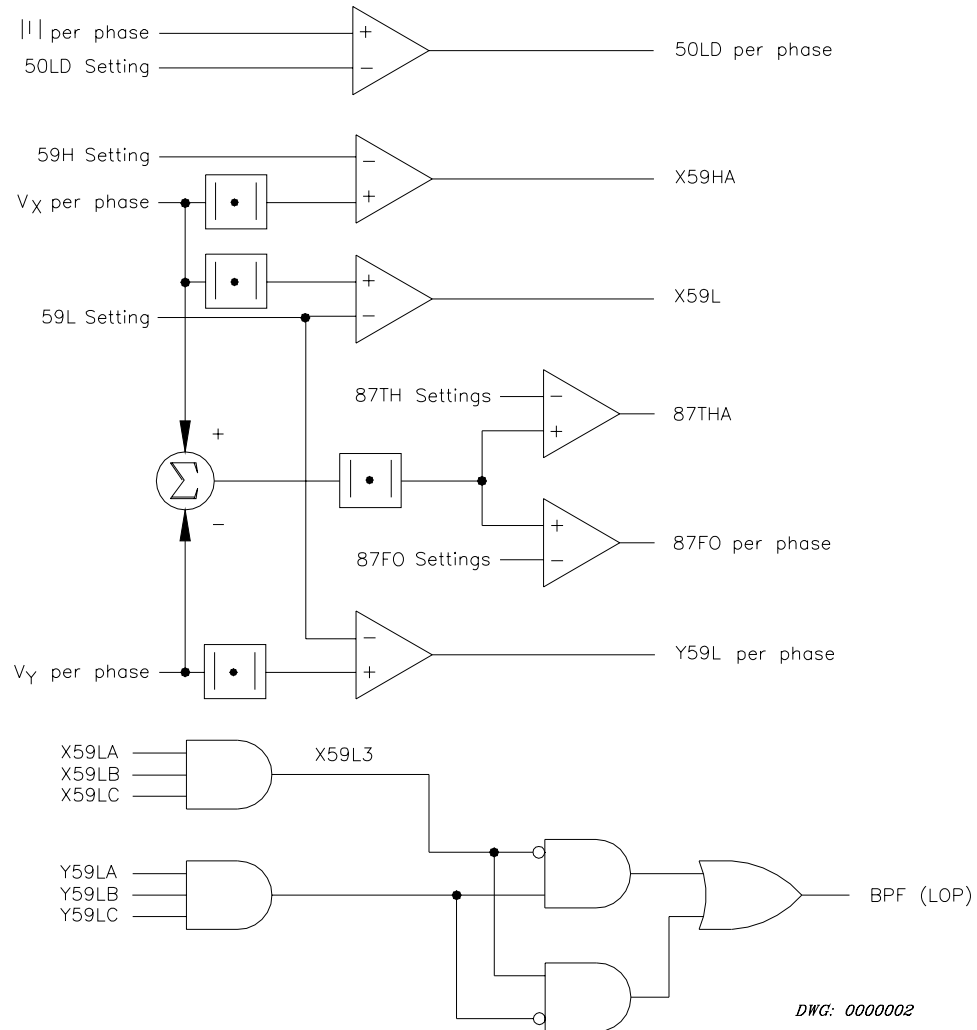


Figure 5: Power System Measurements

Synchronous Conditions

The logic in Figure 6 shows the measurements of the two voltage sources (V_{AX} and V_{AY}) 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.

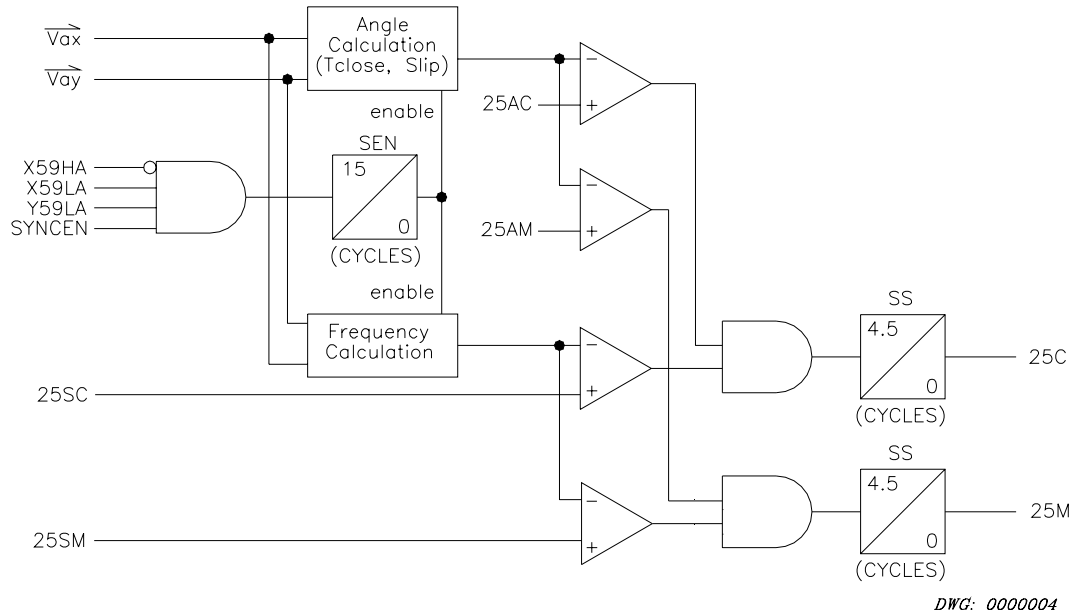


Figure 6: Synchronous Conditions Verification

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 (T_{close}) 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.

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).

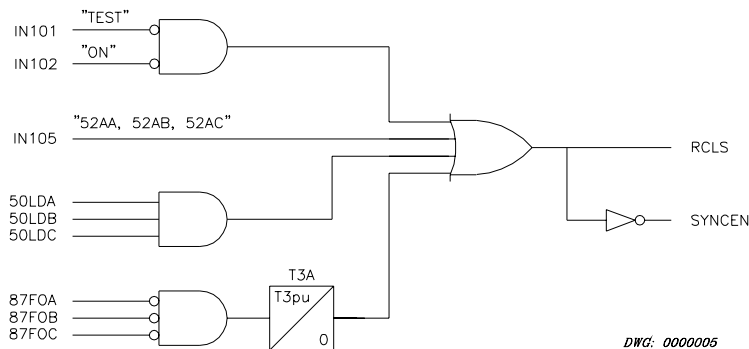


Figure 7: Breaker Closed (RCLS), Scheme Reset Logic

Test Mode and Alarming

The BFTC logic is shown in Figure 8. The control scheme modes of operation, “TEST,” “ON,” and “OFF” (neither asserted), directly supervise any output condition.

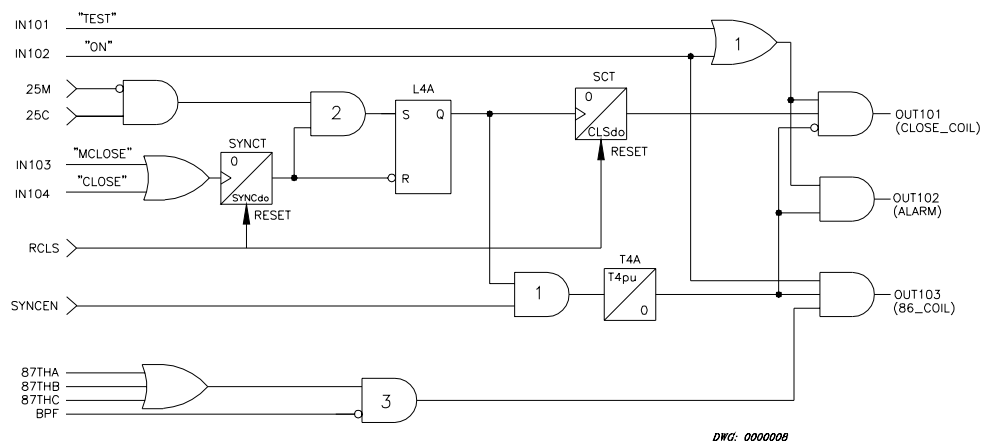


Figure 8: Breaker Failure-To-Close Logic

OFF Mode

When neither the “TEST” nor the “ON” mode is selected, the logic will not close the circuit breaker, assert an alarm, nor energize a lockout relay. The SCT timer will not run because of the reset input from RCLS is asserted, and the T4A timer will not run because SYNCEN is not asserted.

TEST Mode

The intent of the “TEST” mode is to operate the logic under normal conditions, but to have the circuit breaker electrically isolated so that when it closes it does not electrically connect the generator and system. The circuit breaker will either close correctly or the alarm output will assert indicating a slow circuit breaker. The test mode requires a circuit breaker status input to determine when the circuit breaker closes. After opening the circuit breaker, the operation may be repeated until the circuit breaker operates within an acceptable time.

ON Mode

The scheme is fully operational when it is in the “ON” mode. Everything works as in the “TEST” mode except that the alarm output is duplicated to energize a lockout relay for electrically isolating the circuit breaker before it closes if the breaker close operation is too slow.

BFTC Scheme Operation

The scheme shown in Figure 8 is initiated by a close input assertion (CLOSE or MCLOSE). The two separate close inputs allow initiation from another device or from a manual switch. Typical operation would be assertion by the auto-synchronizer for the generator or from an operator controlled switch. When one of these inputs is received, the SYNCT timer is started.

As soon as the synchronous conditions are met (25C) and the generator is slipping at a rate greater than the 25SM setting (25M is not asserted), AND #2 asserts and sets the L4A latch. If synchronous conditions never occur within the SYNCdo time, the L4A latch is reset. After the L4A latch is set, the CLOSE_COIL output is asserted to close the circuit breaker, and the T4A timer is started if SYNCEN is asserted.

If the circuit breaker does not physically close within the T4pu time, the lockout relay (86_COIL) and SLOW_BKR_ALARM are energized. The 86_COIL output is used to open any adjacent circuit breaker or switch to electrically isolate the circuit breaker. The SLOW_BKR_ALARM output energizes a local or remote annunciator.

The difference voltage measurement 87TH also directly supervises the control of the 86_COIL output. This adds security for the scheme. If the system is slipping very slowly and the circuit breaker closes slowly, it still may be within the acceptable angle. In this case, the alarm asserts but the 86_COIL output is not energized until the angle based on the 87TH measurements is beyond acceptable limits. The 87TH supervision of the 86_COIL output is not valid during a blown potential fuse (BPF) condition. Therefore, the 87TH output is disabled when this occurs. The BPF, also known as loss-of-potential condition, can be determined by many methods depending on the device. One method is to use voltage measurements on either side of the circuit breaker to determine X59L3 and Y59L3 as shown in Figure 5. These conditions determine a loss-of-potential condition, which would make the voltage differential measurements invalid. If the loss-of-potential condition is detected, the differential supervision from the 86_COIL output is disabled.

APPLICATIONS

Complete use of this BFTC scheme includes five dc control inputs, three dc control outputs, one set of three-phase ac current inputs, and two sets of three-phase ac voltage inputs. The scheme may be used with a subset of the inputs and outputs with similar results.

DC Connections

Figure 9 shows a typical dc schematic of the BFTC scheme connections. The three-position switch labeled “MODE” asserts the “TEST” and “ON” inputs. The switch labeled “MANUAL CLOSE” is a momentary assertion switch that asserts the “MCLOSE” input. The “CLOSE” input is asserted by the auto-synchronizer close output contact. The circuit breaker auxiliary contact asserts the 52A input when the circuit breaker is closed. The “CLOSE_COIL” output contact is connected to the circuit breaker close coil so that it is energized when the contact closes. The “SLOW_BKR_ALARM” output contact is connected to an annunciator panel, panel lamp, or remote alarm to indicate a slow circuit breaker when the contact closes. The 86_COIL output contact is connected to a lockout relay for tripping other circuit breakers or motor operated disconnects to isolate the synchronizing circuit breaker.

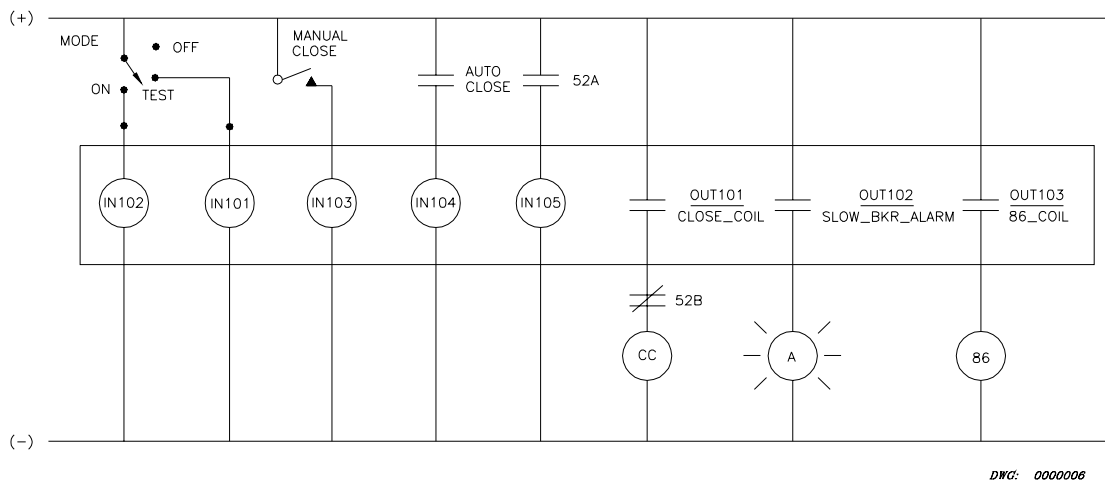


Figure 9: DC Schematic

AC Connections

A typical ac schematic is shown in Figure 10. The three currents are wye connected to current transformers that measure current through the circuit breaker. The three X-side voltages are wye connected to potential transformers on the generator side of the circuit breaker. The three Y-side voltages are wye connected to potential transformers on the system side of the circuit breaker. Use different voltage measurement configurations depending on the installation and available measurement equipment.

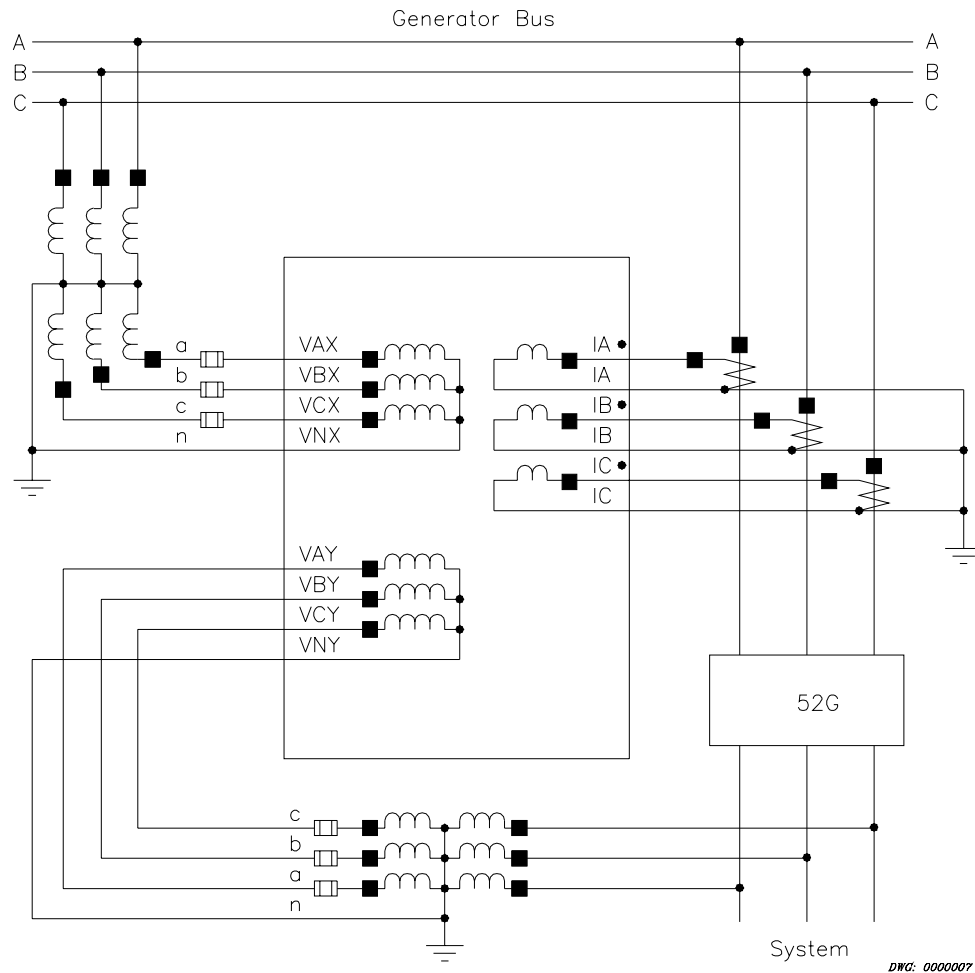


Figure 10: AC Connection Diagram

Installation Costs

The estimated equipment and labor costs for installing this breaker failure-to-close scheme is \$20,000. Actual WE installation costs confirm this estimate. These costs assume that a breaker failure-to-trip scheme is already installed, and all required power system measurements are available.

TEST RESULTS

Laboratory Data

Simulated System Testing

Test equipment capable of generating voltages and currents for injection into the measuring device was used for logic verification. The purpose of these tests was to show that the logic provided 1) an alarm for slow breaker conditions for different slip frequencies, and 2) a varying time for initiation of breaker failure for different slip frequencies. Table 1 shows tests at two frequencies and three breaker operate times. The breaker was intentionally slowed down for the tests. The results are the times the output contacts asserted relative to the breaker close coil energization time. The breaker failure (86_COIL) condition was based on an angle of 22°, which was based on a 30° damage window and a safety margin for time to clear the bus.

Table 1: Simulation Results

		Results (time relative to CLOSE_COIL energization)		
V _{GENERATOR}	Breaker Speed	SLOW_BKR_ALARM	86_COIL	BKR_CLOSED (52A)
60.05 Hz Slip=18°/s	66 ms	No Operate	No Operate	66 ms
	98 ms	88 ms	No Operate	98 ms
	No Close	88 ms	1405 ms	No Operate
60.1 Hz Slip=36°/s	66 ms	No Operate	No Operate	68 ms
	98 ms	88 ms	No Operate	96 ms
	No Close	87 ms	701 ms	No Operate

V_{SYSTEM} was set at 60.00 Hz. The nominal breaker close time was 66 ms. The intended close angle was 3°.

Figure 11 is a screen capture of the sequential event record from the device showing the 60.05 Hz operation when the breaker operated in 98 ms.

SLOW SYNCHRONIZING BREAKER DETECTION					
#	DATE	TIME	ELEMENT	STATE	
1	08/05/97	08:50:18.744	DAMAGE_ANGLE	Asserted	
2	08/05/97	08:50:19.731	CLOSE	Asserted	*Close input asserted by external device
3	08/05/97	08:50:19.749	CLOSE	Deasserted	
4	08/05/97	08:50:21.550	DAMAGE_ANGLE	Deasserted	*Outside of damage angle
5	08/05/97	08:50:22.511	25C	Asserted	*Within anticipated angle
6	08/05/97	08:50:22.517	CLOSE_COIL	Asserted	*Close coil energized
7	08/05/97	08:50:22.601	CLOSE_COIL	Deasserted	
8	08/05/97	08:50:22.605	SLOW_BKR_ALARM	Asserted	*Slow breaker detected
9	08/05/97	08:50:22.615	CURRENT	Asserted	*Breaker closed (current)
10	08/05/97	08:50:22.615	52AA	Asserted	*Breaker closed (52A)
11	08/05/97	08:50:22.617	25C	Deasserted	
12	08/05/97	08:50:22.705	SLOW_BKR_ALARM	Deasserted	
13	08/05/97	08:50:22.923	BKR_CLOSED_87V	Asserted	*Breaker closed (difference voltage)

Figure 11: SER Screen Capture for 60.05 Hz, 98 ms Operation

Figure 12 is an oscillographic and digital display of the device operation. The current was applied by the test equipment to simulate a closed breaker.

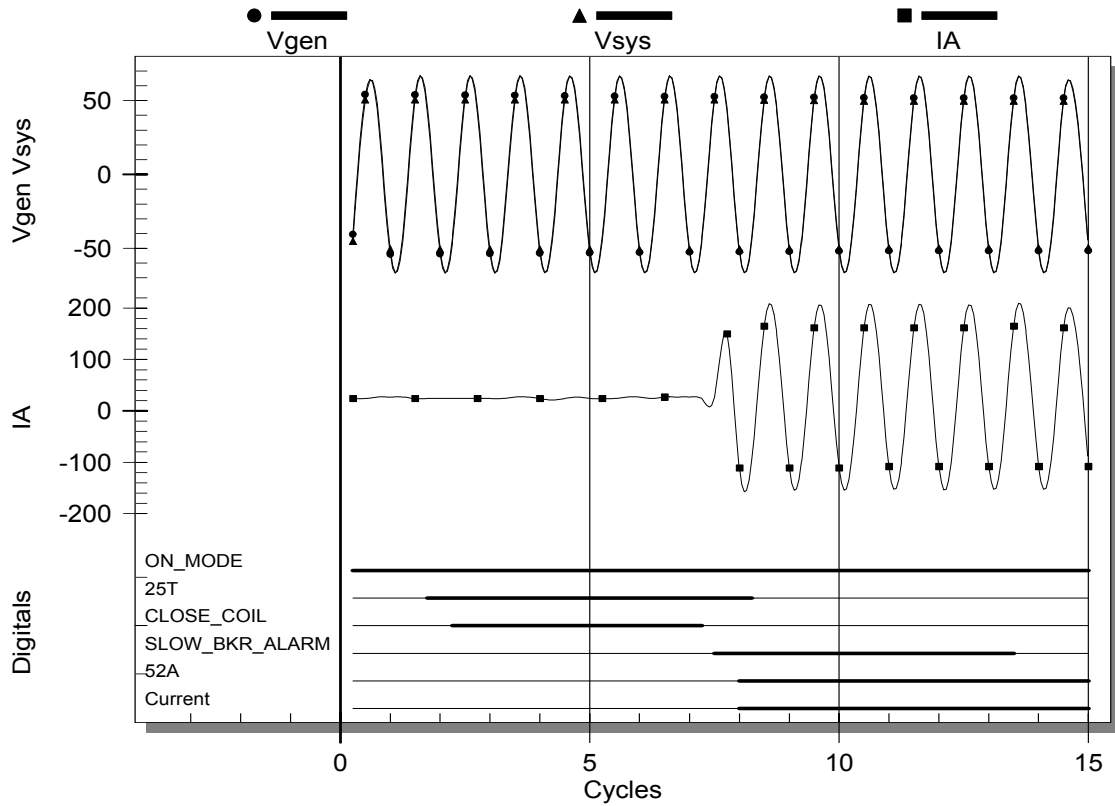


Figure 12: Oscillographic and Digital Display of 60.05 Hz, 98 ms Operation

The simulated system test results showed that the logic worked correctly for all cases. The SLOW_BKR_ALARM asserted at the specified setting, and the 86_COIL asserted when the conditions slipped outside the acceptable window.

Small Laboratory Generator Testing

Simulations were taken one step further by applying the scheme to laboratory machines. A 5 kVA synchronous generator was synchronized to the power system. These tests were intended to prove the same items as the simulations, but the actual current is measured at the time of synchronization. Also, tests were performed to see the change in current based on the closing angle.

Table 2 shows the current magnitude in RMS due to synchronizing at the various angles. The current is very dependent on the type of machine and system conditions. These results are intended only to verify that as close angle increases, the transient conditions on the generator and system increase, increasing the possibility for damage.

Table 2: Transient Current for Different Close Angles

Closing Angle	RMS Current
Generator leads system by 4°	16 Amps
Generator leads system by <1°	7 Amps
Generator lags system by 4°	12 Amps
Generator lags system by 11°	25 Amps
Generator lags system by 19°	42 Amps
Generator lags system by 24°	59 Amps

Figure 13 shows the case when the breaker closed with the two systems 24° out of phase. Current reached 59 Amps within the first half cycle before the systems were pulled together.

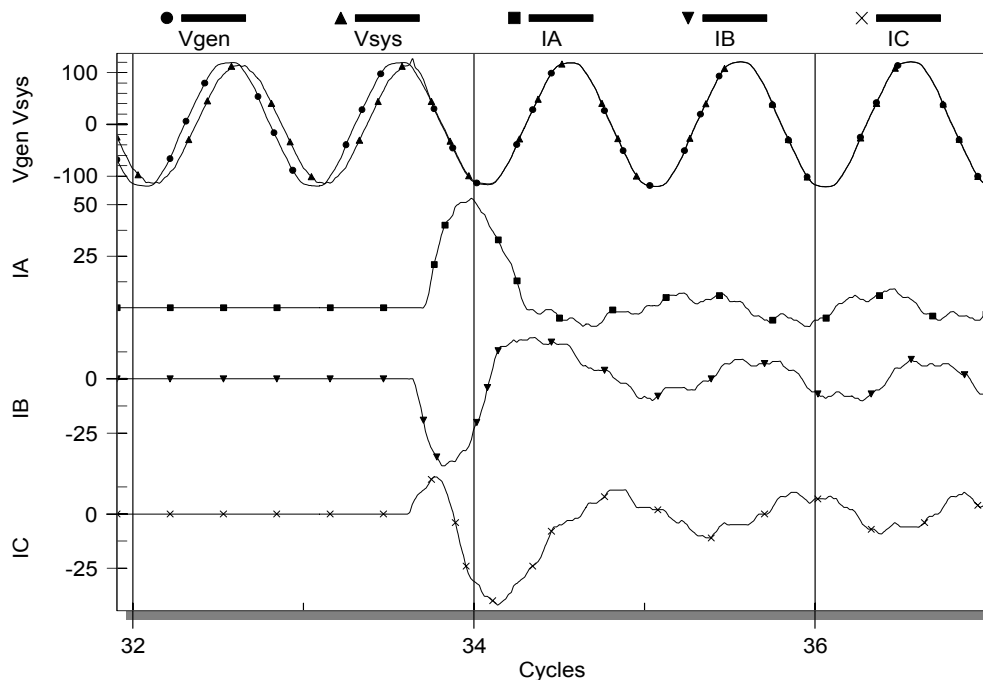


Figure 13: Oscillographic and Digital Display of 24° Close Operation

Table 3 shows the results of tests at 59.85 Hz at three breaker operate times. The breaker failure (86_COIL) condition was based on an angle of 10° based on a 13° damage angle window and a safety margin for time to clear the bus.

Table 3: Laboratory Machine Results

V _{GENERATOR}	Breaker Speed	Results (time relative to CLOSE_COIL energization)		
		SLOW_BKR_ALARM	86_COIL	Current
59.85 Hz	22 ms	No Operate	No Operate	27 ms
Slip=54°/s	189 ms	30 ms	No Operate	194 ms
	388 ms	30 ms	314 ms	Breaker closed into a dead bus in 390 ms

V_{SYSTEM} was set at 60.00 Hz. The nominal breaker close time was 22 ms. Intended close angle was 8°.

Figure 14 is a screen capture of the sequential event record from the device showing the operation when the breaker operated in 390 ms. The large transient current was avoided by clearing the bus prior to the breaker closing.

SLOW SYNCHRONIZING BREAKER DETECTION

#	DATE	TIME	ELEMENT	STATE
12	09/11/97	10:17:55.328	MCLOSE	Asserted
13	09/11/97	10:17:55.829	MCLOSE	Deasserted
14	09/11/97	10:17:57.417	DAMAGE_ANGLE	Deasserted
15	09/11/97	10:17:57.517	25C	Asserted
16	09/11/97	10:17:57.528	CLOSE_COIL	Asserted
17	09/11/97	10:17:57.557	SLOW_BKR_ALARM	Asserted
18	09/11/97	10:17:57.742	25C	Deasserted
19	09/11/97	10:17:57.842	DAMAGE_ANGLE	Asserted
20	09/11/97	10:17:57.842	86_COIL	Asserted
21	09/11/97	10:18:04.293	DAMAGE_ANGLE	Deasserted
22	09/11/97	10:18:04.293	86_COIL	Deasserted
23	09/11/97	10:18:04.395	25C	Asserted
24	09/11/97	10:18:04.622	25C	Deasserted
25	09/11/97	10:18:04.727	DAMAGE_ANGLE	Asserted
26	09/11/97	10:18:04.727	86_COIL	Asserted

Figure 14: SER Screen Capture of 390 ms Close Operation

Figure 15 is an oscillographic and digital display of the 390 ms breaker operation. The breaker finally closed after the 86_COIL was energized and the bus was cleared. The measured system voltage does not go to zero because of the potential transformer location for the test.

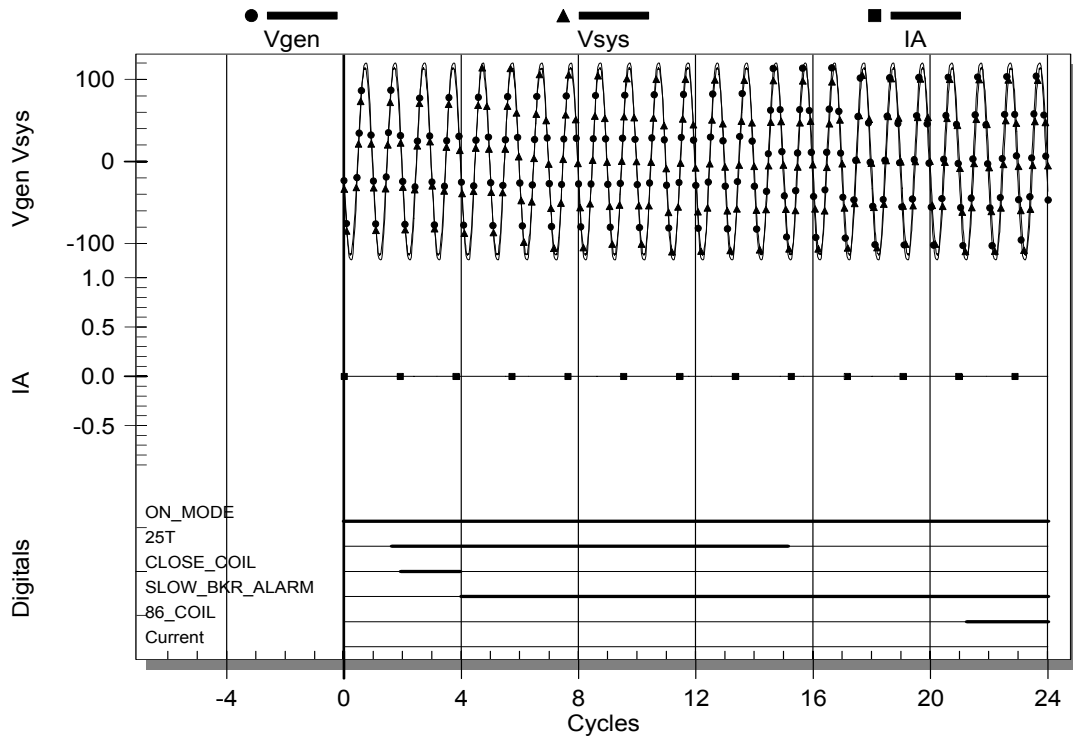
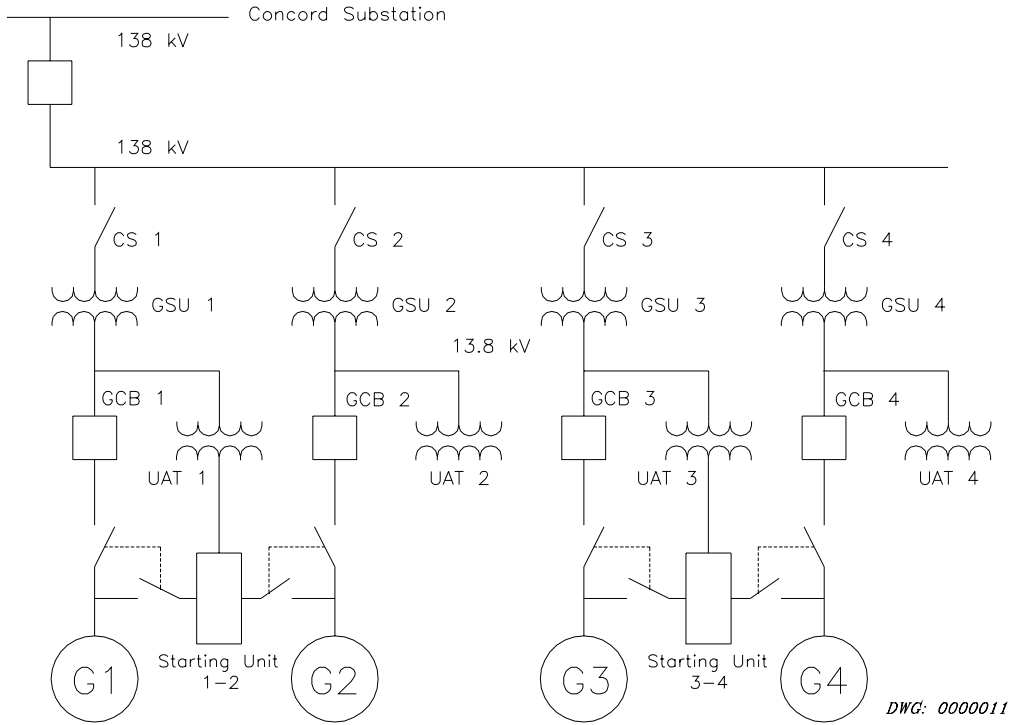


Figure 15: Oscillographic and Digital Display of Breaker Failure-To-Close Operation

The small laboratory generator test results showed that as the close angle increases, more current flows to synchronize the two systems. These tests also verified the logic.

Field Data

Field tests were performed by Wisconsin Electric at the Concord Generating Station. Concord Generating Station is a combustion turbine plant with four units. Refer to Figure 16 for a single line diagram of the station. Each unit has the following ratings: 119.2 MVA, 0.8 pf, 13.8 kV, 3600 RPM. They are each connected to a common 138 kV bus through a 13.8 kV generator breaker; a generator step-up transformer (GSU) rated at 13.8 - 138 kV, 60/80/100 MVA; and a 1200 A circuit switcher. The common 138 kV bus is connected to the system at the Concord Substation bus through a 138 kV oil circuit breaker. Each unit is started as a motor by a static frequency converter starting unit, that is switched out when combustion is established. The unit is then synchronized through the 13.8 kV generator breaker. The measuring device was connected in a monitoring mode. All inputs, outputs, and internal logic were monitored. No output contacts were actually connected to the breaker failure scheme. Concord generator's synchronizing breaker could not be isolated so the "TEST" mode was not implemented.



**Figure 16: Single Line Diagram of Concord Generating Station
Wisconsin Electric Power Company**

Figure 17 shows the voltage and current of a synchronizing operation. All close operations of the Concord generator breaker were successful closures so the scheme never indicated a slow breaker condition or initiated breaker failure.

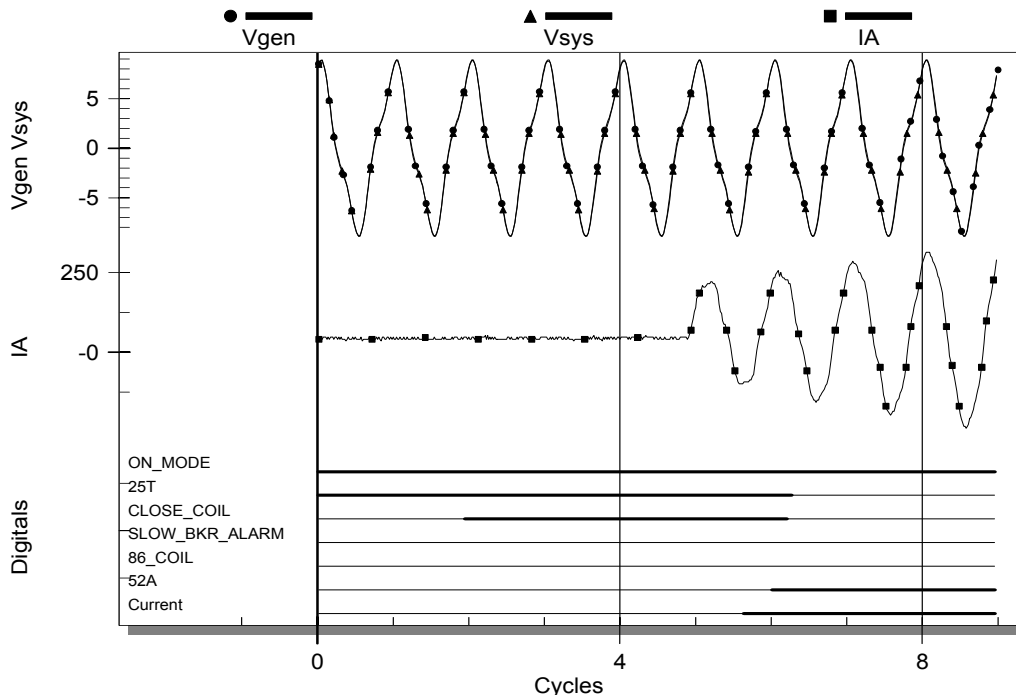


Figure 17: Concord Generator Breaker Synchronous Close Operation

Figure 18 shows a summary of the breaker close operations for the Concord installation. The 14 operations since June 2, 1997, were all within breaker specifications. The breaker showed minimal variation mechanically (based on the 52A contact). Electrically (based on current) the breaker showed a variation of about one cycle. This variation is associated with the amount of current when the breaker closes. The breaker trip operations were not monitored.

OPERATION SUMMARY FROM 06/02/97						
	TRIPA	TRIPB	TRIPC	CLOSEA	CLOSEB	CLOSEC
Number of Operations	0	0	0	14	14	14
Ave. Elect. Time (ms)	0.0	0.0	0.0	69.3	75.4	77.5
Ave. Mech. Time (ms)	0.0	0.0	0.0	67.1	67.1	67.1
Last Elect. Time (ms)	0	0	0	66	87	89
Last Mech. Time (ms)	0	0	0	66	66	66

Figure 18: Concord Generating Station Breaker Timing Report

CONCLUSIONS

1. A single device can provide synchronous closing control and supervision after an auto-synchronizer brings a generator up to speed, and provide secure, reliable breaker failure-to-close protection.
2. The breaker can be considered closed based on the auxiliary breaker contact, voltage angle difference (delta voltage), and/or initial synchronizing power flow.
3. Generator and system damage can reliably be avoided by implementing a breaker failure-to-close scheme.
4. Security from unnecessary bus clearing operations by the breaker failure-to-close scheme are avoided by verifying voltage angle difference (delta voltage) prior to operation.
5. A test mode to operate and time the breaker prior to synchronization is easily implemented as part of a breaker failure-to-close scheme.
6. A breaker failure-to-close scheme is easily adapted to various system arrangements and synchronizing operation methods including manual and automatic closing.

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