New Voltage-Based Breaker Failure Scheme for Generators

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NEW VOLTAGE-BASED BREAKER FAILURE SCHEME FOR GENERATORS

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Abstract

Many abnormal operating conditions can cause significant damage to a generating system if not cleared properly. Traditional breaker failure schemes measure current to indicate if the breaker has failed to open. This signal is too small to be a reliable indication of breaker status for many generator protection elements. The present accepted practice in the industry is to use the mechanical 52a breaker status as a supplement to the current detector to maintain the breaker failure timer. This paper describes a new breaker failure scheme for generator breakers that is based on voltage measurements to detect the failure of a generator breaker to open and separate the generator from the power system. The new scheme can be applied for generator breakers in conjunction with the traditional current-based breaker failure scheme to eliminate the need to rely on mechanical breaker status indication. The system relies on measuring synchronism parameters between voltage signals on either side of the breaker to determine if the breaker has failed to open. These parameters originate in the synchronism-check function resident in the generator protection relay. The paper discusses details of the scheme and application and operation considerations relative to generating plant bus topology.

1 Introduction

Protection of synchronous generators is very different from protection of most other elements of the power system. With lines, buses, and transformers, the protection engineer can focus on detecting short circuits with significant current flow that must be detected and cleared quickly to limit damage and prevent loss of stability. Generators, on the other hand, are very costly and complex electromechanical systems. Short-circuit detection is, of course, equally as important as for other elements of the power system. But, most of the protection schemes that the protection engineer must apply to a generator relate to detecting abnormal operating conditions that can damage the electrical machine and/or the prime mover if not cleared. Many of these abnormal operating conditions can occur with very low current flowing in the generator's main breaker. Traditional current-based breaker failure schemes can fail to detect failure to open when the generator is tripped for an abnormal operating condition.

The importance of correct breaker failure operation cannot be overstated. A failure to quickly isolate the generator puts both the machine and the power system at risk. On the other hand, an unnecessary breaker failure operation can result in the loss of multiple generators and could lead to an extensive power system outage.

While true abnormal operating condition trips are rare, many generators are routinely taken offline by a process called sequential tripping. In a sequential trip shutdown, the prime mover is tripped to intentionally motor the generator. The generator breaker is then opened by a reverse power relay that detects this motoring condition. This is done to ensure that all sources of mechanical power have been removed. For example, if the steam valves of a steam turbine generator have not seated properly, leaving a small steam flow on the turbine, the generator can freely spin to damaging overspeed once it is no longer in synchronism with the power system. Steam turbines in particular can be quickly damaged during an overspeed event. By opening the generator breaker using a reverse power relay, the possibility of such a situation is eliminated. However, if the intentional motoring condition should continue because the breaker failed to open, the prime mover can be damaged in less time than an operator can typically analyze the situation and trip adjacent breakers manually. The current presented to the breaker failure relay during a motoring event for a steam turbine can be in the order of 0.33% of its nominal rating [1]. Intentional motoring during normal shutdown will occur many times over the life of the generating system.

To ensure breaker failure systems for generator breakers are dependable for abnormal operating condition trips, industry guidelines show using mechanical indication of breaker closed status (52a auxiliary contact) to maintain the breaker failure timer in addition to the traditional current detector [2]. In many cases the transmission owner and the generator owner are separate entities. Often, the transmission breaker failure protection system is designed by the transmission owner who may not be familiar with the special requirements of generator breaker failure systems. There have been cases of generator system damage because the breaker failure system did not include a 52a contact. To help raise awareness, [3] was recently updated to include a separate clause dedicated to the special requirements of breaker failure systems applied to generator breakers.

Because a mechanical indication is prone to both dependability and security failures, an electrical measurement can be more reliable [4]. This paper describes a new breaker failure scheme for generator breakers that is based on voltage measurements to detect the failure of a generator breaker to open and separate the generator from the power system.

2 Review of Breaker Failure Concepts

Breaker failure schemes include the AND combination of two signals along with a delay timer [3]. The first signal indicates that the breaker has been commanded to open to disconnect electrical power system elements to alleviate a short circuit or abnormal operating condition. The second signal indicates whether the breaker is open or closed. The logic can be simply described as follows: if the breaker has been commanded to open and does not open in a reasonable time, trip all adjacent breakers to disconnect the electrical power system element.

The most common signal to indicate whether the breaker is still closed after being commanded to open is a measurement of the current through the breaker. The 50BF element is alternatively set as a fault detector (above load) to ensure that the 62BF timer only asserts for fault conditions to enhance security; or, as a current detector (at minimum) to detect breaker opening [3]. Even when set as a current detector, this signal is an unreliable indication for many generator protective trips. The magnitude of the current during a generator motoring event and for other potentially damaging conditions can be smaller than a relay's ability to determine that the breaker has failed to open.

Fig. 1 shows the scheme logic for a typical generator breaker failure system. The addition of the mechanical breaker indication to the traditional current-based breaker failure scheme offers, in theory, the solution to low-current breaker failure detection. However, the mechanical indication through the breaker 52a auxiliary contact is not infallible. The indication is from a mechanical representation of the breaker status and is part of the mechanical system being monitored for failure [4]. Note that additional features of a modern breaker failure protection scheme such as retrip and trip seal-in are omitted from the figures in this paper.

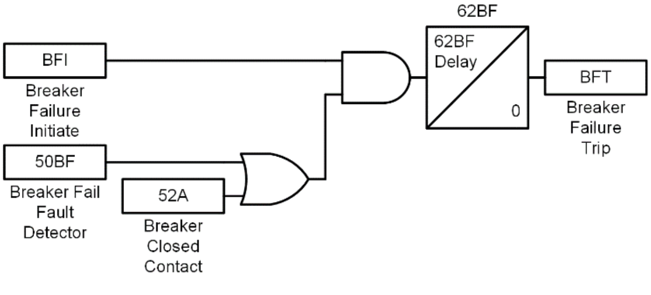

Fig. 1. Typical generator breaker failure scheme logic.

The mechanical indication is provided by breaker auxiliary contacts from a rotating cam that is directly linked to the breaker mechanism. In many generating plant applications, auxiliary relays are used to multiply the breaker status indication contacts. Often, the distance between the main breaker and the generator protection and control circuits is quite large, so an auxiliary relay to replicate the breaker status contacts is used to reduce the length and voltage drop in the circuits as well. This often adds an additional component that can fail to the system. A 52a contact (rather than a 52b) has typically been used since control wiring open circuits or auxiliary relay failures are among the more common breaker status failure modes.

Failure of the mechanical indication of breaker status can result in both dependability and security failures of the breaker failure protection system. If the mechanical indication falsely indicates that the breaker is still closed when it has properly opened, a security failure occurs, and adjacent elements of the power system are tripped unnecessarily. If the mechanical indication falsely indicates that the breaker is open when it is not, a dependability failure occurs, and the generating system associated with the breaker can be severely damaged. A more reliable system for detecting that a generator breaker has failed to open is required.

Breaker failure protection schemes must always be designed for high reliability with a bias towards security, given the disruptive effect that backup tripping can have on the power system. To improve reliability, an electrical measurement to confirm a failure-to-open condition is preferred over a mechanical indication.

3 25BF, Synchronism Check Breaker Failure

3.1 Synchronism-Check (25) Relays

Synchronism-check (25) relays are normally used to supervise the closing of generator breakers. A synchronism-check relay typically monitors the angle of voltage signals on both sides of a breaker. A modern microprocessor-based synchronism-check relay that is suitable for generator synchronizing applications directly measures the three critical parameters of synchronism [5] defined in (1), (2), and (3).

$$F_{\text{INCOMING}} - F_{\text{RUNNING}} = \text{SLIP} \quad (1)$$

$$\left(\frac{V_{\text{INCOMING}} - V_{\text{RUNNING}}}{V_{\text{RUNNING}}} \right) \bullet 100 = \text{VDIF}_{\%} \quad (2)$$

$$\text{ANG}_{\text{INCOMING}} - \text{ANG}_{\text{RUNNING}} = \text{ADIF} \quad (3)$$

where:

INCOMING is the generator signal.
RUNNING is the bus signal.
F is the measured frequency.
SLIP is the difference in frequency.
V is the measured voltage magnitude.
$\text{VDIF}_{\%}$ is the difference in magnitude in percent.
ANG is the measured angle.
ADIF is the difference in angle.

When these three parameters are within set synchronism acceptance criteria, the synchronism-check relay provides a permissive signal to allow the breaker to close. It is good practice to only enable the synchronism-check relay when the breaker is open as the three parameters of synchronism will always be satisfied when the breaker is closed. We want the synchronism-check relay to start measuring the three synchronism parameters only when the breaker is open such that the permissive transitions from de-asserted to asserted.

3.2 Synchronism-Check Breaker Failure (25BF) Protection

If the generator has zero slip, zero voltage difference, and zero angle difference across the main breaker, it is a good indication that the generator is connected to the power system. The 25BF scheme uses these criteria to confirm that the generator main breaker has failed to open. Fig. 2 shows the logic to detect that the generator remains synchronized to the power system. Reasonable tolerance bands around zero are used to account for inherent magnitude and angle errors in the instrument transformer circuits. Checking the errors is recommended. This can be done by enabling the synchronism check element while the breaker is closed.

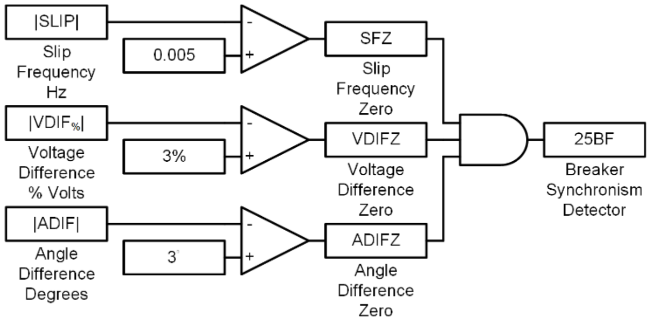

Fig. 2. Three parameters of synchronism.

The 25BF element is used similarly to the 50BF element or the 52A bit as shown in Fig. 1 to determine that the breaker has failed to open and allow the breaker failure timer, 62BF, to time out.

Once a generator has separated from the power system, all three of the checks that indicate synchronism will de-assert in a fairly short period of time. The scheme logic requires only one check to de-assert. For separations that involve load rejection, the accelerating force is large, and the slip and angle will diverge from zero very rapidly. But, for this type of trip, 50BF schemes are effective. The worst-case scenario for using synchronism measurements to detect failure to open is a generator during a sequential trip. The mechanical power provided by the prime mover is purposely zero so forces to move the generator out of synchronism are small. Steam and hydro turbines often have very high inertia and low windage losses, which will contribute to possible slow divergence of the three synchronism parameters. For this reason, the breaker failure scheme logic in Fig. 1 is modified as Fig. 3 to include a separate timer for these low-current trips.

Including a separate initiate and timer allows the breaker failure protection system to be optimized for security. The protection engineer can initiate the 50BF scheme for all or some of the protective elements and only initiate the 25BF scheme for those protective elements that require the voltage-based scheme such as from 24, 32R, 59P, 63SPR, 64G, and 64F. In the next section, breaker failure initiate (BFI) considerations are discussed more fully.

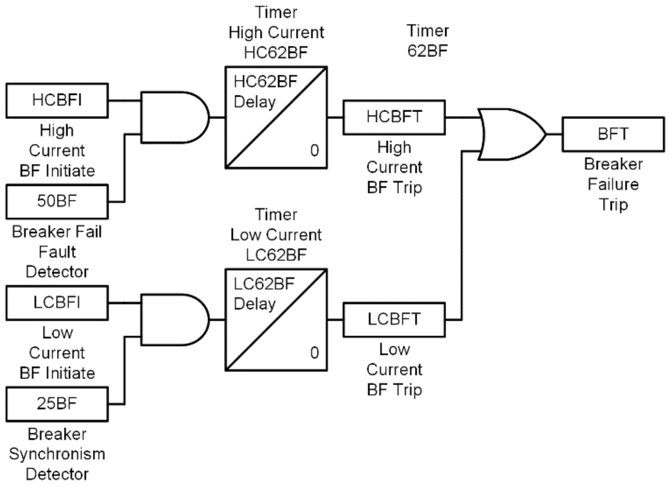

Fig. 3. New generator breaker failure scheme.

The allowable time for clearing a fault (HCBFI with 50BF supervision) is extremely short. For faults, we often require minimum HC 62BF timer margin (the margin between the expected time for the breaker to interrupt and declaring it has failed) to keep the system stable. Typical settings for this timer are 6 to 10 cycles. On the other hand, abnormal operating condition trips allow more time so a longer time to allow the 25BF element to de-assert is acceptable. For example, the recommended time for tripping a steam turbine generator for a motoring condition is in the range of 10 to 30 seconds [2]. A typical setting for the LC 62BF timer is in the range of 15 to 60 cycles.

Similar to the practice of initiating a normal shutdown during the initial commissioning startup process of a generator and measuring the actual motoring power to fine tune the setting of the reverse power relay, the time to de-assertion of the 25BF element during a normal shutdown can be used to fine tune the LC 62BF timer setting. Even with a large time margin, the 25BF scheme can still separate the generator more quickly than an operator using manual intervention.

Fig. 4 shows a simulation of a successful sequential trip of a 60 Hz steam turbine generator. We can see that the 25BF bit de-asserts in 80 ms (4.8 cycles) after the BFI asserts. The first element to de-assert is SFZ. ADIFZ de-asserts in 234 ms (14.0 cycles) and VDIFZ de-asserts in 285 ms (17.1 cycles). In this case, 25BF only took 1.3 cycles to de-assert after the main contacts opened, as can be observed by the current traces. Thus, the scheme is not appreciably slower than the 50BF scheme. However, we suggest conservative settings given that slower operation is acceptable for these low-current trips.

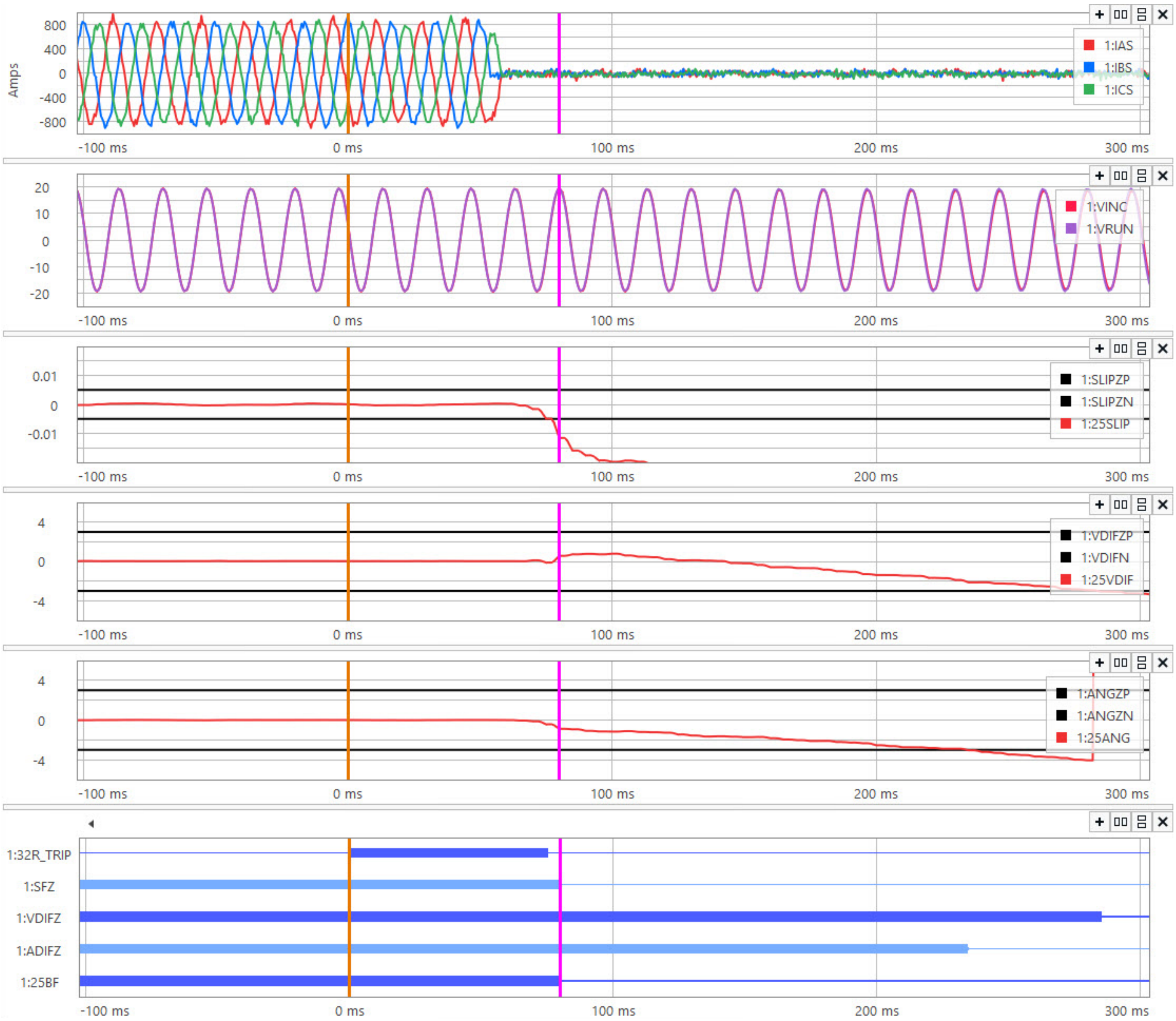

Fig. 4. Simulated normal shutdown.

4 Application Considerations

In this section, we discuss practical considerations for applying the 25BF scheme. We cover applications where the generator has a single main breaker connecting it to the power system and applications where the generator has dual breakers connecting it to the power system.

Because every breaker separates two zones of protection, the breaker will be tripped by protection systems for the generating system and the protection systems for the adjacent zones. The new scheme has two BFI inputs. For this reason, we also advise on considerations for designing the BFIs for the two schemes.

4.1 Single-Breaker Applications

The scheme is quite straightforward when applied to a single-breaker application. If the single breaker fails to separate the generator from the power system, the failure can be selectively determined by either current signals (50BF) or voltage signals (25BF). Both supervisory conditions will stop their respective timers to prevent a breaker failure trip.

For a bus fault in a single-breaker (straight bus) application, the bus protection will typically directly initiate a simultaneous trip of the generator (simultaneously trip all sources of energy to the generation system including the main breaker, field breaker, prime mover, and transfer auxiliary power). Initiating the breaker failure scheme from the bus protection is often not done because in straight bus applications all the same breakers are tripped for a switchyard bus fault as for a breaker failure. There are no special considerations for initiating the two schemes from the protective trips. For applications that do not use sequential tripping from a 32R relay, the manual trip to take the generator offline should initiate the 25BF scheme.

4.2 Dual-Breaker Applications

Applications that have two breakers connecting the generator to the power system are less straightforward. Examples include ring bus, breaker-and-a-half bus, and double-bus/double-breaker arrangements. These bus configurations are popular because they provide greater resiliency and tolerance for failures of power system elements. Using voltage signals to detect a breaker failure to open has the inherent limitation that, unlike current signals, voltage signals alone do not provide selectivity to determine which breaker failed to open and separate the generator from the power system. If one breaker fails to open, the voltage signals on the system side of the breaker that successfully opened will remain in synchronism with the generator side signals through the adjacent bus paths.

Fig. 5 shows a typical breaker-and-a-half bus arrangement that we will use to illustrate the application of the new 25BF scheme. We will focus on G1, CB1, and CB2. If a trip signal is given to CB1 and CB2 to protect G1 and one of the two breakers fails to open, the 25BF element indicates this failure but cannot determine from voltage alone which breakers to open to properly isolate the generator.

As with most protection schemes, there are tradeoffs to consider between security and dependability. We must consider the mode and consequences of damage that the protection is designed to prevent, as well as the consequences of the actions taken to prevent the damage. [4]

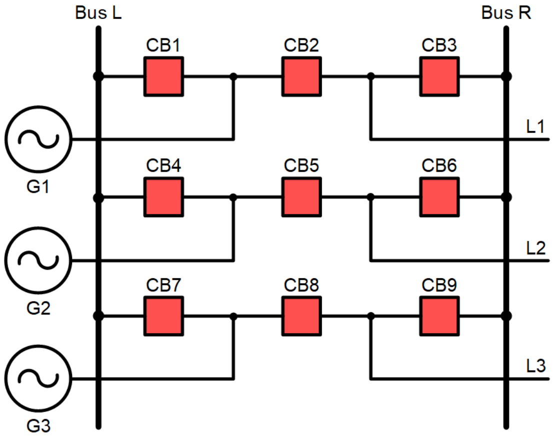

Fig. 5. Dual-breaker application example.

For dual-breaker applications, the 25BF scheme is applied as shown in Fig. 6 and Fig. 7. The scheme is modified to include an additional timer and uses the breaker 52a status to steer the breaker failure trip to improve selectivity. Although this seems to offer no advantage over the original 52BF scheme shown in Fig. 1, the new scheme enhances both security and dependability over using 52a status only. The dual-breaker 25BF scheme only uses the 52a indication to steer BFT after the 25BF element has determined that the generator has not been separated from the system. This offers improvement over the mechanical-only breaker failure tripping logic for security failures of the 52a contact [4].

The DB62BF timer then runs concurrent with the two LC62BF timers and is set with a delay twice that of the LC62BF timers. If both 25BF elements indicate that the generator is still connected to the system, both zones are cleared to prevent damage to the generator system. This logic offers improvement over the mechanical-only breaker failure tripping logic for dependability failures of the 52a contact.

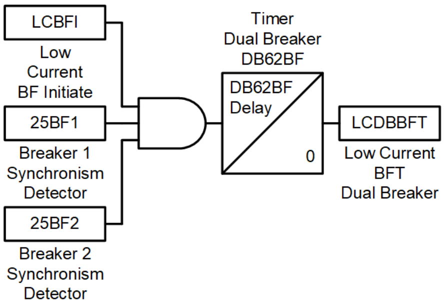

Fig. 6. Dual-breaker scheme logic.

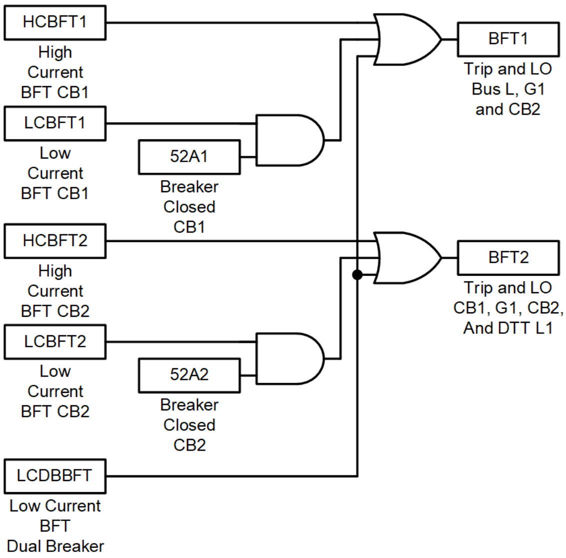

Fig. 7. Dual-breaker tripping logic.

This example illustrates one of the benefits of a breaker-and-a-half bus arrangement [4]. Referring to Fig. 5, incorrectly isolating both Bus L and Line 1 only removes one network element (generator or line) from the transmission grid, which is no worse than what would happen if CB2 experienced a breaker failure and everything worked correctly [4]. So, the new breaker failure scheme significantly improves protection of the generator system from damage for a breaker failure incident without major adverse effects to the grid [4].

In dual-breaker arrangements, it is important to arrange the BFIs such that only generator shutdown trips [4] initiate the 25BF scheme. Trips that do not take the generator offline, such as manually tripping only one of the two breakers, should not initiate the new scheme because the unit remains in synchronism. Similarly, if relays protecting the adjacent zone (Bus L or Line L1 in the Fig. 5 example) initiate tripping of the shared breaker, the generator remains in synchronism with the power system through the other breaker.

This guidance also applies to either of the low-current breaker failure schemes (52BF and 25BF). To help bias the generator breaker failure scheme towards security, initiate all fault trips (line, bus, transformer, and generator) where 50BF is dependable to that BFI input. Route only the generator abnormal operating condition trips to the low current BFI input.

Further, using the raw protective element for LCBFI is recommended [4]. This provides a second means of de-asserting LCBFT and stopping the DB62BF timer from timing out. Once the generator is successfully separated via breaker failure tripping, the BFI path may de-assert more quickly than the 25BF element, which can reduce the DB62BF timer setting required. We can see this in Fig. 4. The BFI signal, 32R_TRIP, de-asserts 5 ms before 25BF. Otherwise, if the BFI is initiated from the generator lockout status, the DB62BF timer should be set similarly to the LC62BF timer.

5 Conclusion

Generator protection involves many protection elements that detect abnormal operating conditions that can result in costly damage [4] to the complex electromechanical generating system. Some of these abnormal operating conditions can be accompanied by very low current flow through the generator breaker. Reverse power protection is one such protection element that is often used for normal shutdown of a steam turbine generator via a process known as sequential tripping. This scheme operates many times over the life of the system. Motoring a steam turbine generator while drawing only a few milliamperes of secondary current in the relay circuit can cause significant damage to the turbine [4].

The time to damage is much longer than for a fault but less than the time for an operator to manually respond. Traditionally, current detection has been supplemented with mechanical detection of breaker status using a 52a contact to detect a generator breaker failure condition [4]. Mechanical protection can suffer from both dependability and security failure modes [4]. A synchronism-check-based element provides an electrical measurement to confirm that the generator has not been separated from the power system.

Traditional current-based breaker failure protection is important to provide fast clearing of faults that can cause significant damage or cause the system to become unstable. But, 50BF schemes fail to protect the generator for many abnormal operating condition trips. Breaker failure schemes must be designed with high reliability but with a bias towards security as they will be called upon to restrain much more often than they will be called upon to trip.

Dual-breaker bus arrangements require special application consideration because voltage measurements cannot provide the selectivity to identify which of the two breakers failed to open. In such applications, the use of 52a status and an additional timer can provide an overall improvement in both security and dependability relative to a 52BF scheme.

6 Acknowledgements

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