Adaptive Loss-of-Field Protection Tailored to the Generator Capability Curve

Matchyaraju Alla, Armando Guzmán, Dale Finney, and Normann Fischer
Schweitzer Engineering Laboratories, Inc.

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ADAPTIVE LOSS-OF-FIELD PROTECTION TAILORED TO THE GENERATOR CAPABILITY CURVE

Matchyaraju Alla[1*], Armando Guzmán[1], Dale Finney[1], Normann Fischer[1]

[1]Schweitzer Engineering Laboratories, Inc., Pullman, Washington, USA
**matchyaraju_alla@selinc.com*

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Abstract

Loss of field (LOF) occurs when the generator field winding provides insufficient excitation voltage for proper generator operation, causing the generator to operate outside its desirable operating region. During an LOF condition, in cylindrical-rotor (turbo) generators, the leakage flux flows perpendicular to the stator laminations, generating eddy currents that heat up the end core of the stator. Fast disconnection of the generator during this condition minimizes the generator's stress and maintains power system stability. This paper presents implementation details of a generator protection scheme with characteristics tailored to the generator capability curve (GCC) of the machine. The scheme provides improved generator protection and simplifies the coordination of scheme elements with the generator underexcitation limiter (UEL) and the steady-state stability limit (SSSL) of the generator.

1 Introduction

A complete or partial loss-of-field (LOF) condition can occur because of an open or short circuit in the field circuit, an excitation failure, an operation error, or such a power system event as loss of auxiliary power supply services. Generator loading and power system strength can impact the response of the generator to LOF conditions. Potential generator damage and/or loss of power system stability greatly depends on these factors. Consequently, design and application of LOF protection are one of the more challenging aspects of generator protection.

1.1 Effect of an LOF on a Synchronous Generator

Reduction of the field current weakens the magnetic coupling between the stator and rotor and can lead to a loss of synchronism. If the generator loses synchronism, it will overspeed and operate asynchronously. The pre-fault loading is a determining factor in the final value of slip. Slip induces damaging currents into the amortisseur (damper) windings of the rotor and the body of the rotor. It can also induce high voltage into the field winding for an open field circuit, which could result in insulation damage of the field winding. The turbines that drive cylindrical-rotor generators are often very sensitive to overspeed and can be damaged quickly. While slipping poles, the generator can absorb reactive power equal to as much as twice its rated megavolt-amperes (MVA). This increase in power absorption can quickly overload the stator.

Fig. 1 shows a cut-away view of a cylindrical-rotor generator. When the field current decreases, the rotor retaining rings that hold the field winding transition from a saturated state to an unsaturated state. As a result, the reluctances of the paths between the core ends and the rotor decrease. This decrease results in increased fringe, axial flux flowing between the stator-end-core regions and the rotor retaining rings [1].

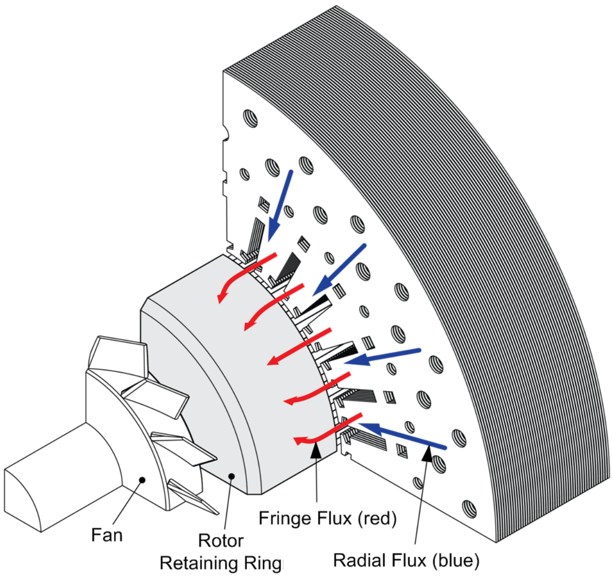

Fig. 1. The fringe flux (shown in red) between the stator-end-core region and the retaining ring increases when the rotor retaining ring comes out of saturation.

The fringe flux linking the stator core rotates at the generator synchronous speed, but it is stationary with respect to the rotor. Therefore, the fringe flux causes circulation of eddy currents and losses in the stator-end-core laminations; there is neither circulation of eddy currents nor losses in the rotor retaining rings.

The heat that the fringe flux generates can melt the stator-core lamination within minutes. The heat that the stator-end-core region can dissipate before being damaged determines the reactive power that a cylindrical-rotor synchronous generator can absorb. Hence, the stator end-core heating limit (SECHL), not the stator current heating limit, determines the reactive power lower limit of the generator capability curve (GCC) for cylindrical-rotor synchronous generators. Note that end-core heating, described previously, does not occur in salient-pole generators.

1.2 Effect of LOF on the Power System

During an LOF event, the generator draws significant reactive power to maintain the flux in the air gap between the generator stator and rotor. This reactive power consumption can jeopardize power system stability.

Furthermore, a loss of synchronism can cause large pulsations in voltages and currents at the generator terminals and negatively impact system stability.

1.3 Adaptive Generator Protection Scheme

This paper (a shortened version of [2]) proposes an improved generator protection scheme that consists of four protection zones:

- Zone 1. A fast protection trip element with a straight-line characteristic defined in the P-Q plane to detect LOF conditions when the generator is consuming significant reactive power.
- Zone 2. A delayed protection trip element with a characteristic that can be tailored according to the underexcitation limiter (UEL) characteristic. Undervoltage conditions accelerate the operation of this element.
- Zone 3. An alarm and trip element with a characteristic defined in the P-Q plane based on the steady-state stability limit (SSSL). This element is intended to trip when the operating point enters Zone 3 and the automatic voltage regulator (AVR) is operating in manual mode or during undervoltage conditions.
- Zone 4. An alarm element with a characteristic defined in the P-Q plane based on the GCC limits. This element expands and contracts dynamically, using measurements from the generator's cooling system.

2 Generator Capability Curve

The GCC defines the generator operating limits in the P-Q plane, as shown in Fig. 2. The following factors determine the GCC:

1. The current rating (thermal limit) of the field winding imposes the limit on the generator reactive power export capability (GCC overexcited region, Segment ① in Fig. 2).
2. The current rating (thermal limit) of the stator winding imposes the limit on the generator active power output at near unity power factor (Segment ② in Fig. 2).
3. The generator type determines the GCC underexcited region limit (Segment ③ in Fig. 2): SECHL limits the reactive power import of most cylindrical-rotor generators. The current rating (thermal limit) of the stator winding limits the underexcited region of salient-pole generators. Salient-pole generators with direct-axis synchronous reactance, X_d, less than 1.0 pu only have two limits (Segments ① and ② shown in Fig. 2). However, the SSSL is generally more restrictive than the stator winding thermal limit of the generator and therefore typically defines the generator underexcitation limit.

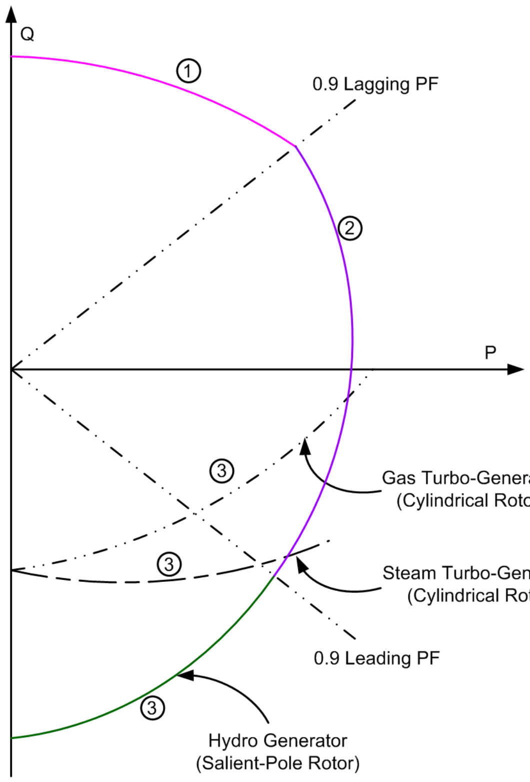

Fig. 2. GCCs for cylindrical-rotor and salient-pole-rotor generators.

Synchronous generators can have multiple ratings depending on their coolant: ambient air or hydrogen. Generator manufacturers specify the GCC based on coolant temperature (ambient air) or pressure (hydrogen) typically above and below the generator-rated temperature or pressure, as shown in Fig. 3. When the generator uses hydrogen, a greater coolant pressure increases the operating range of the generator and vice versa.

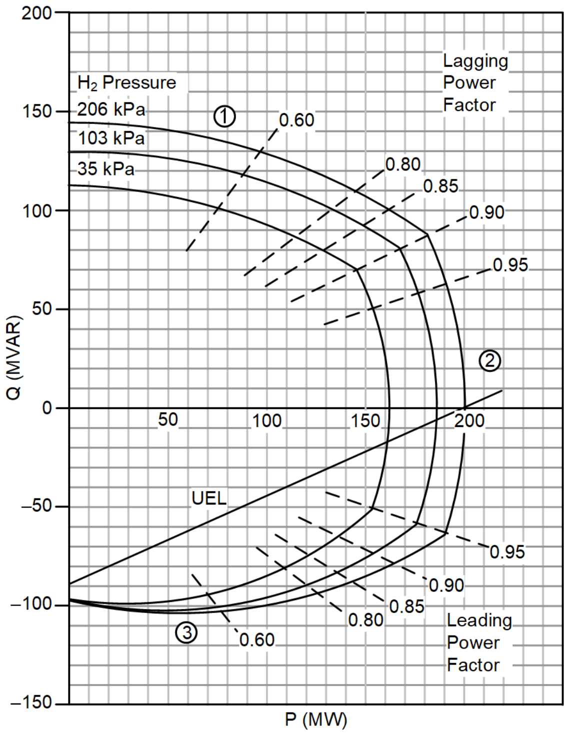

Fig. 3. GCC at nominal voltage of a 202 MVA, 15 kV, 0.9 pf, 3600 rpm, 60 Hz, hydrogen-cooled steam-turbine generator for various hydrogen pressures.

3 P-Q Plane-Based LOF Element

In this section, we describe a new LOF protection scheme based on the GCC defined in the P-Q plane. The scheme comprises three LOF protection zones and a GCC alarm zone, as shown in Fig. 4.

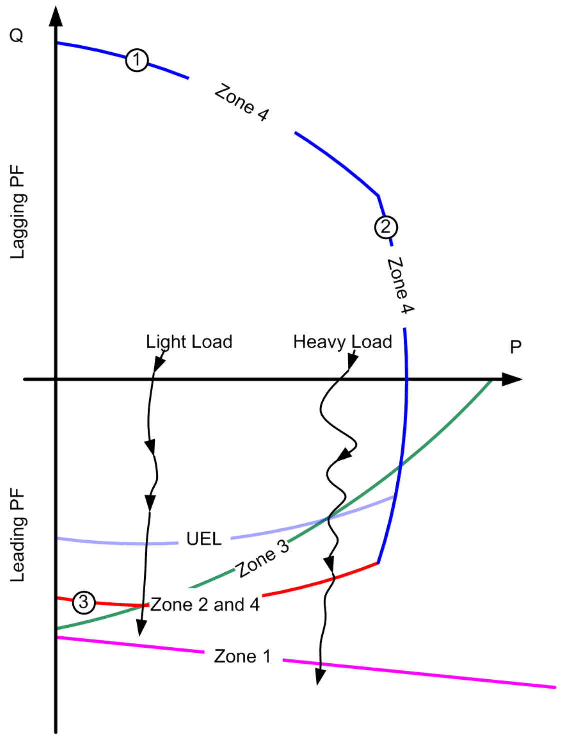

Fig. 4. P-Q-based LOF function with four zones.

3.1 *Zone 1 Trip Element*

When an LOF condition occurs on a strong power system, the system supplies the generator with reactive power. If the generator is heavily loaded before the LOF condition, the generator draws significant reactive power from the system. This condition could impact generator stability as the generator transitions from synchronous to asynchronous operation. Zone 1 is defined in the P-Q plane as a straight line, but it operates in the admittance plane. As shown in Fig. 4, the operating point moves quickly into Zone 1 for these loading conditions. Zone 1 is intended to operate quickly for severe LOF events (e.g., open circuit in the field winding).

The Zone 1 characteristic and delay can be set following the traditional LOF element practice. The Zone 1 delay is typically set short enough to prevent generator damage for an LOF at full load, but long enough to avoid tripping it for stable power swings [3] [4] [5].

3.2 *Zone 2 Trip Element*

The Zone 2 element operates for LOF events at light loads. It also provides thermal protection during underexcited operation. The UEL governs the underexcited operation of the generator. There are a variety of UEL characteristics that have been modeled in [6]. In the P-Q plane, the UEL characteristic shifts proportionally to V_T^k, where V_T is the terminal voltage and k can be equal to 0, 1, or 2.

For instance, the IEEE UEL1 characteristic is a circle that changes according to V_T^2 ($k = 2$). The IEEE UEL2C characteristic is either a single straight line or a multisegmented characteristic; it can be configured to be either independent of V_T ($k = 0$), dependent on V_T ($k = 1$), or dependent on V_T^2 ($k = 2$).

The Zone 2 element can be tailored according to the UEL characteristic and includes a margin and a K-factor *(k)* setting to coordinate with the UEL characteristic. Furthermore, the Zone 2 element can adapt to changes in the generator cooling capability if the UEL supports this adaptability.

Zone 2 delay is set short enough to prevent generator damage for an LOF condition at low loads but long enough to avoid tripping for stable power swings. A delay setting in the range of 1 to 60 s is recommended. As with the impedance schemes, the Zone 2 element can be set to have an accelerated trip during field or terminal undervoltage conditions. A delay in the range of 0.25 to 0.5 s may be used during undervoltage conditions ($V_T < 0.8$ pu as per [7]). Stable power swings or UEL dynamic response can cause Zone 2 operation during these conditions, so determination of an optimal delay setting requires detailed power system studies [8].

3.3 *Zone 3 SSSL Alarm and Trip Element*

In weak power systems, the SSSL characteristic could encroach into the GCC. For proper coordination, the Zone 3 element is based on the replica of the SSSL characteristic and is set according to (1), where X_d and X_S (the system equivalent reactance) are settings. The Zone 3 characteristic is defined as a circular segment in the P-Q plane bounded within the 3rd and 4th quadrants. The characteristic is implemented in this plane but operates in the admittance plane. Note that some AVRs use (1) to implement the UEL characteristic.

$$Z3_{pu} = \mathrm{Re}\left(\left((P + jQ) - \frac{j3 \bullet V_T^2}{X_S}\right) \bullet \left(\frac{-j3 \bullet V_T^2}{X_d} - (P + jQ)\right)^*\right) \quad (1)$$

The Zone 3 characteristic always moves in synchronism with the SSSL characteristic, so it does not lose coordination with SSSL when V_T changes.

Zone 3 picks up and instantaneously alarms when the operating point approaches or crosses the SSSL characteristic. Because loss of steady-state stability may not occur when the AVR and power system stabilizer are in service, the operator can correct this alarm condition. Additionally, when Zone 3 picks up, it issues a trip command after a short delay if the AVR operates in manual mode or $V_T < 0.8$ pu.

Note that SSSL is meaningful when the AVR operates in manual mode. If the AVR provides an indication that it is in manual mode, this indication can be routed to the Zone 3 element to supervise tripping of the generator. Alternatively, an actual loss of steady-state stability should be accompanied by a significant undervoltage condition ($V_T < 0.8$ pu) [7]. Therefore, Zone 3 includes a dedicated undervoltage supervision element to accelerate tripping regardless of the AVR operating mode. A pole slip can occur quickly, so the delay should be set on the order of 0.25 s.

The traditional Zone 2 element of the impedance scheme in [4] is often set to coordinate with the SSSL characteristic. In the proposed scheme, Zone 3 is dedicated to coordinate with the SSSL characteristic, and Zone 2 is dedicated to coordinate with the UEL characteristic. Therefore, setting Zone 2 requires no compromise.

3.4 Zone 4 GCC Alarm Element

The GCC alarm function uses the three segments identified as ①, ②, and ③ in Fig. 4 to implement a digital replica of the GCC. One of the algorithms in the scheme fits one curve for each segment of the GCC. Furthermore, the algorithm can model Segment ③ by using either piece-wise-linear or quadratic curve fitting to accommodate various GCCs with either straight-line or circular characteristics.

P and Q coordinates define each segment. Many generators have GCCs that expand and contract according to the generator cooling level. The algorithm is designed to shrink and expand the GCC replica based on an analog measurement of the cooling capability or a binary input (if available), as shown in Fig. 5.

In this case, we enter the coordinates of the minimum GCC (identified with circular dots in Fig. 5) along with the maximum GCC coordinates (identified with diamonds in Fig. 5).

The Zone 4 element is intended to provide an alarm whenever the generator operates close to the GCC limits. This element does not trip the generator, so its delay can be set in the range of 1–10 s to minimize the occurrence of spurious assertions.

Segment ③ of Zone 4 can be set between the UEL and Zone 2 characteristics to issue an alarm before the operating point reaches Zone 2. Segment ③ dynamically coordinates with the UEL and Zone 2 characteristics based on the corresponding K-factor setting. A properly configured Zone 4 characteristic can also vary with the generator cooling capability.

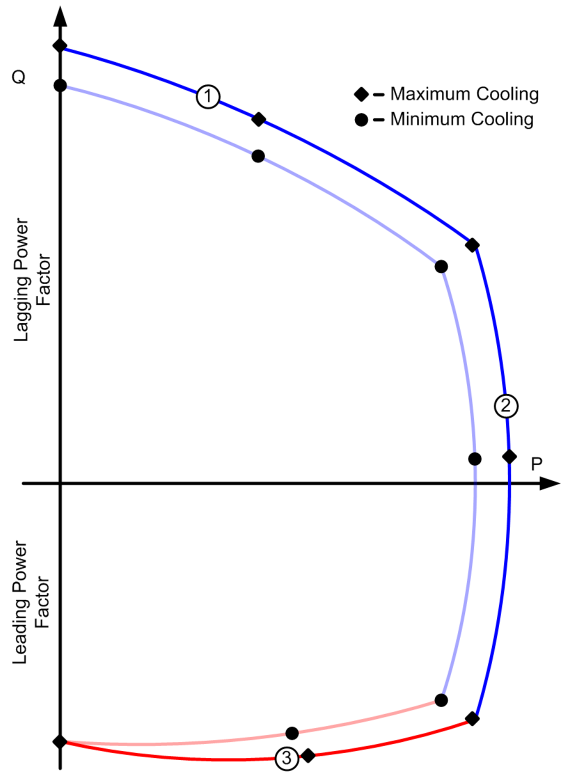

Fig. 5. Adaptive GCC replica based on cooling capability.

3.5 Coordination of LOF Elements With the UEL Characteristic During Terminal Voltage Variations

The K-factor of Zone 2 and Segment ③ of Zone 4 allows for proper coordination with the UEL for V_T changing conditions.

3.5.1 UEL and LOF Characteristics for k = 0

Fig. 6 shows one approach for coordination of Zone 2, Zone 4, and UEL characteristics with $k = 0$. Let us consider a voltage-independent UEL ($k = 0$) with a two-straight-line characteristic set with a 10 percent margin with respect to Segment ③ of the GCC. According to the proposed scheme, Zone 2 follows the UEL settings but, because it has a margin setting of 10 percent, it is at Segment ③ of the GCC. Optionally, for alarming, Segment ③ of Zone 4 can be set with 5 percent margin with respect to the GCC. For $k = 0$, the UEL, Zone 2, and Zone 4 characteristics are static in the P-Q plane, and the Zone 3 characteristic varies in proportion to V_T^2.

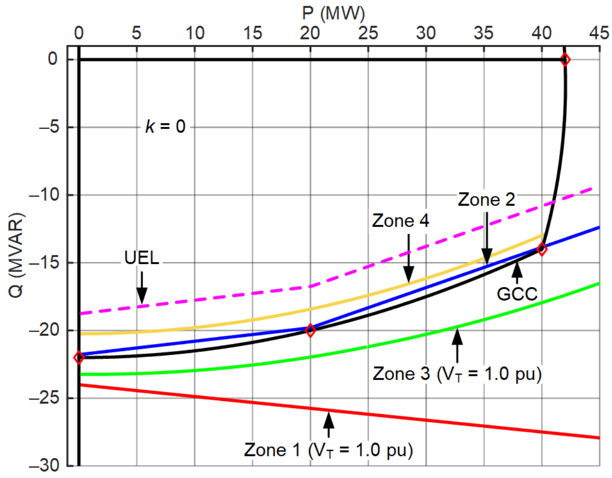

Fig. 6. UEL and LOF characteristics for $k = 0$.

3.5.2 *UEL and LOF Characteristics for k = 1*

Fig. 7 shows the coordination of Zone 2 and UEL characteristics for the $k = 1$ setting. The figure also shows the UEL and Zone 2 characteristics for $V_T = 1$ and 0.85 pu, and the Zone 3 characteristic for $V_T = 0.85$ pu. Note that for V_T changes, the Zone 2 characteristic moves in the same way as the UEL characteristic.

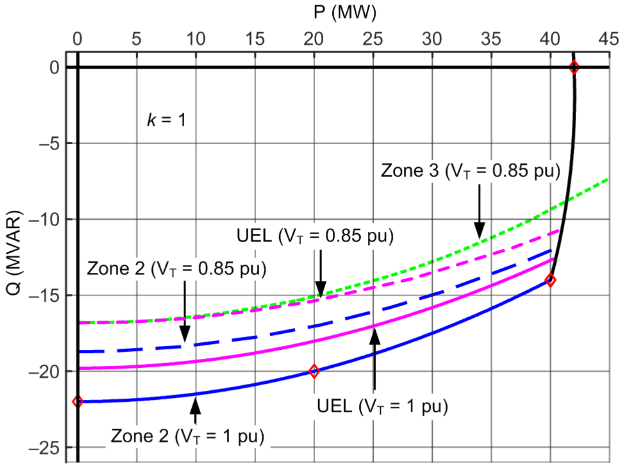

Fig. 7. UEL and LOF characteristics for $k = 1$.

When $V_T < 0.8$ pu and the operating point is inside the Zone 3 characteristic, if the AVR fails to correct the low-voltage condition, Zone 3 times out and issues a trip command to prevent the generator from slipping poles. With this approach, schemes with $k = 0$ or $k = 1$ accelerate tripping during severe undervoltage conditions (e.g., $V_T < 0.8$ pu) via Zone 3.

3.5.3 *UEL and LOF Characteristics for k = 2*

SECHL changes according to V_T and X_d [9] [10], so the UEL characteristic should be set above the SECHL at $V_T = 1.05$ pu for proper coordination when $k = 2$, as shown in Fig. 8. For $k = 2$, the margin between the UEL characteristic and the GCC should be no less than 15 to 20 percent at $V_T = 1.0$ pu.

Set Zone 2 with respect to UEL so it has a margin of 5 to 10 percent to protect the generator when $1.0 \text{ pu} < V_T \leq 1.05$ pu. With this margin, Zone 2 provides protection for end-core heating during overvoltage conditions, but it decreases the generator operating capability at rated voltage. This problem is typically more pronounced in combustion gas turbines where the SECHL is extremely restrictive, as shown in Fig. 2. If, however, Zone 2 is set to match the GCC, it will not provide adequate protection for the generator when $1.0 \text{ pu} < V_T \leq 1.05$ pu (see the highlighted portion in Fig. 8).

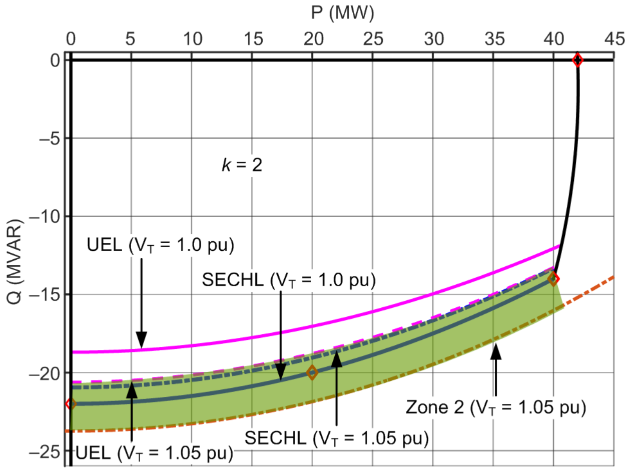

Fig. 8. UEL characteristic for $k = 2$ and SECHL.

4 Summary

In summary, the key features of the proposed LOF protection and monitoring scheme are as follows:

- All the zones are set in the P-Q plane, using the generator GCC and data sheet.
- Zone 1 and Zone 3 operate in the admittance plane and account for changes in V_T.
- Zone 2 and Segment ③ of the Zone 4 characteristic coordinate with the UEL characteristic by means of their corresponding K-factor settings.
- Zone 2 trip can be accelerated during severe LOF conditions accompanied by undervoltage ($V_T < 0.8$ pu).
- Zone 3 issues an alarm when the operating point approaches or crosses the SSSL characteristic and issues a trip during undervoltage conditions ($V_T < 0.8$ pu).
- Zone 3 can also trip with a short delay when the operating point approaches or crosses the SSSL characteristic and the AVR operates in manual mode.
- Zone 4 issues an alarm when the operating point is close to the GCC limits, which can change according to the cooling level.
- Studies for determining proper delay settings of Zone 1 and accelerated Zone 2 (when $k = 2$) and Zone 3 should be performed in the admittance plane.

5 Conclusion

The first generation of LOF protection schemes was developed decades ago. At that time, excitation systems and AVRs were simpler and power system stability was the major concern. Legacy LOF protection schemes provided good operating speed for most LOF events and were secure for external faults and power swings. They used electromechanical technology, so implementation was also simple. However, these legacy schemes left room for improvement [4] [5] [11] [12].

This paper introduces a new LOF protection scheme that provides better protection without sacrificing the advantages of legacy implementations. The proposed scheme is built around the concept of a GCC replica. Generator capability changes with cooling conditions. Modern generators have instrumentation that provides analog indication of the cooling condition. The scheme can use these analog measurements to dynamically expand and contract the GCC replica.

SECHL is a problem for cylindrical-rotor machines and it varies with V_T. Modern UELs can shift their characteristics to match the GCC. The Zone 2 and Zone 4 elements this paper introduces have characteristics that can shift in the same direction and degree as the UEL characteristic. This adaptation allows for a smaller margin between the UEL and LOF element characteristics, resulting in better protection for the generator.

LOF schemes also provide protection against loss of steady-state stability, and for this reason legacy schemes are often coordinated with the SSSL characteristic in addition to the UEL characteristic, which may compromise the generator LOF protection. The new LOF scheme includes a dedicated zone (Zone 3) to coordinate with the SSSL characteristic for improved coordination without sacrificing generator protection.

Finally, the new LOF scheme is defined in the P-Q plane, which eases setting of elements. You can enter the required scheme settings with the values obtained from the generator data sheet. Additionally, a graphical user interface displays the relay characteristics and provides assurance that the scheme is properly configured. This approach reduces the possibility of setting errors.

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