Antimotoring Protection With Dependability-Biased Characteristic

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Presented at the
13th International Conference on Developments in Power System Protection
Edinburgh, United Kingdom
March 7–10, 2016

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Keywords: synchronous generator, generator protection, reverse power, current transformer error.

Abstract

When a steam turbine loses steam flow, it can no longer supply power to the system and instead draws enough power from the system to meet its windage and frictional losses. This condition, known as motoring, can cause damage to the turbine. Directional power relays are used to detect the motoring power into the electrical machine and open the generator's main breaker to prevent damage from this abnormal operating condition. The motoring power for large steam turbines can be a very small fraction of the power rating, leading to sensitivity issues and failure to detect and trip for this condition. A directional power relay may operate dependably during normal sequential trip shutdown sequences where the real and reactive power output is ramped down to zero prior to tripping the turbine. In this case, the power factor is near unity, and the relay has little difficulty in measuring the real power component of the signal. However, during a true inadvertent motoring event, the reactive power output may remain at near pre-event levels, resulting in a significant MVA output at near-zero power factor. During these conditions, small angle errors in the instrument transformers and measuring devices can result in large errors in measuring the very small real component of the apparent power flow. This paper describes a new directional power algorithm in the form of an adaptive characteristic that provides a dependability bias to ensure tripping during an inadvertent motoring event.

1 Introduction

When a generator loses its prime mover while connected to the power system, it begins to draw power from the network to supply its losses. This condition does not present a risk to the generator; however, there is a risk of damage to the prime mover. The amount of power drawn (motoring power) depends on the machine type. Motoring power (P_M) is often expressed as a percentage of rated power. The motoring power of reciprocating engines and combustion turbines is relatively high. The motoring power of a hydrogenerator is high or low, depending on whether the tail race water level is above or below the turbine blades. Motoring power can be 0.2 to 2 percent for the latter case. A steam turbine that motors under full vacuum also presents a very low motoring power of 0.5 to 3 percent.

Microprocessor relays are now commonly applied for generator protection. Often, the same current transformer (CT) is used for both reverse power detection and for the balance of the generator protection functions. The minimum current detection requirement can be very low. For example, assuming that the CT primary is 120 percent of generator rated current, that the generator voltage is 105 percent of rated voltage, and that the generator is motoring at 0.5 percent at unity power factor, the current seen by the relay is 0.33 percent of its nominal rating. Assuming a 1 A nominal rated CT, The relay must accurately measure a current of only 3.3 mA. In order to provide a margin for error, typically the reverse power element pickup is set at 50 percent of expected motoring power [1]. Often, the actual motoring power is measured during initial start-up commissioning procedures and adjusted accordingly.

For a motoring event with the machine operating at unity power factor, the magnitude of the current can be very low. Generator relays are designed to measure this low current value. Small angle measurement errors are not a problem. However, if the expected motoring power is very low and the generator also produces significant reactive power, an angle error can result in a loss of dependability [1] [2] [3]. This is illustrated in Fig. 1, where an angle error can shift the measured power to the point shown by the red triangle.

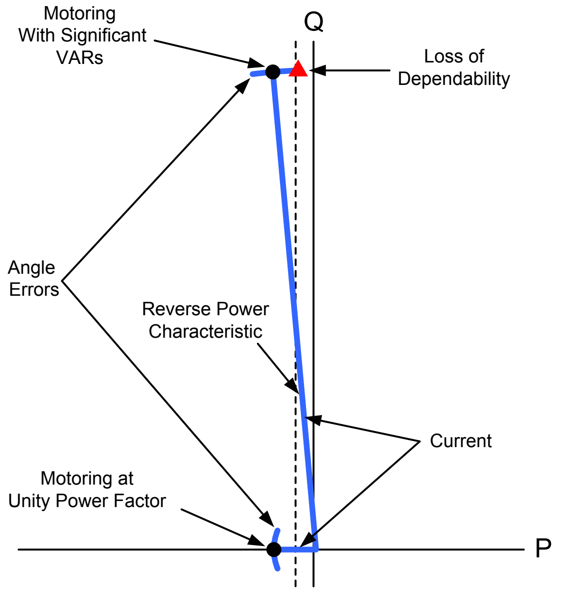

Fig. 1. Angle error impact during motoring.

Because the relay is usually calibrated to minimize internal sources of angle error, the primary source resides with the instrument transformers, i.e. CTs and voltage transformers (VTs).

The following method can be used to estimate angle error. If one assumes that the generator operates initially at rated MVA with a power factor of 0.85 and that the reactive power remains constant during a motoring event, the reactive power is:

$$Q_M = \sqrt{1-0.85^2} = 0.527 \,. \tag{1}$$

Assuming a P_M of 0.5 percent,

$$\theta_M = \tan^{-1}\left(\frac{0.527}{0.005}\right) = 89.456 \text{ degree} \,. \tag{2}$$

Assuming a reverse power pickup setting of ½ P_M, or 0.25 percent,

$$\theta'_M \approx \tan^{-1}\left(\frac{0.527}{0.0025}\right) = 89.728 \text{ degree} \,, \tag{3}$$

and

$$\theta_{ERR} = \theta'_M - \theta_M = 0.27 \text{ degree} = 16 \text{ minutes} \,. \tag{4}$$

It is concluded that a loss of dependability can occur for an angle error as minor as 0.25 degree and that many installations may be vulnerable to poor dependability during an inadvertent motoring event. While inadvertent motoring events are rare, there have been incidents of failure to trip, requiring operator intervention to separate the generator from the power system. Reverse power protection systems that have been proven to work dependably over many normal shutdowns may not provide the expected protection during an inadvertent motoring event. This paper describes a new directional power algorithm in the form of an adaptive relay characteristic that provides a dependability bias to ensure tripping during an inadvertent motoring event.

2 Generator response during a motoring event

Typically, when the generator is connected to the power system, the automatic voltage regulator (AVR) is configured to maintain rated voltage at its terminals. Limiters in the AVR ensure that the reactive power produced by the machine remains within the generator's capability curve as shown in Fig. 2.

During a controlled shutdown of the generator, the AVR is usually switched to operate at unity power factor.

During a manual shutdown and some abnormal operating condition (non-fault) trips, the generator is often allowed to intentionally motor to avoid overspeed when the generator breaker opens. The reverse power relay is used to confirm that the steam valves are fully closed and seated and that there is no steam flow that can cause the turbine to speed out of control once the generator is no longer locked to the synchronous speed determined by the system frequency. This process is known as sequential tripping. The AVR should also be switched to unity power factor operation during sequential tripping to ensure dependable operation of the reverse power element.

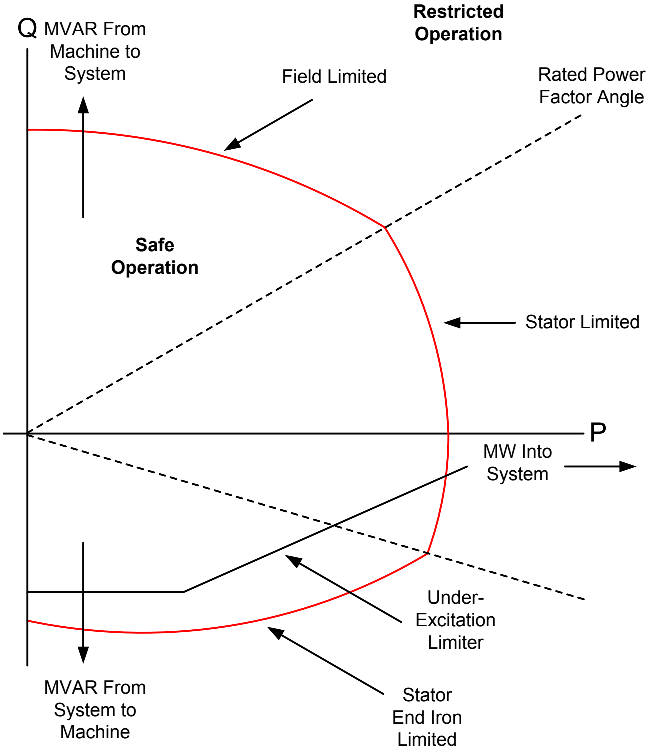

Fig. 2. Generator capability curve.

During an inadvertent motoring event, if the AVR continues to regulate the generator terminal voltage, the reactive power can be significant and the generator real and reactive power output follows the locus shown in green in Fig. 3. This is the scenario in which dependability may be lost.

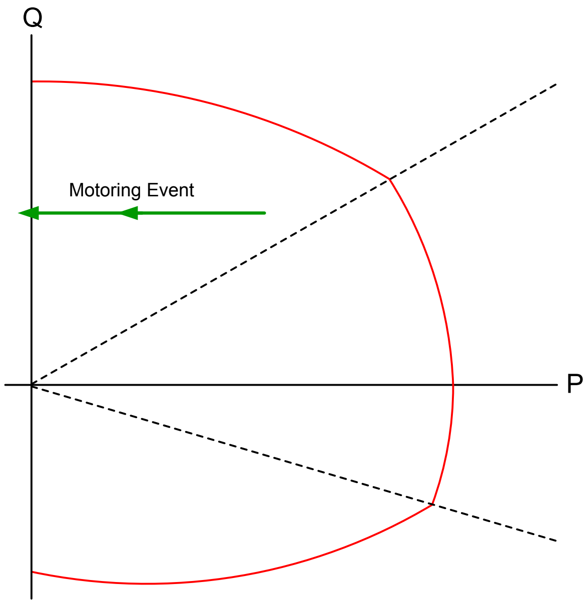

Fig. 3. Inadvertent motoring event.

Fig. 3 is a simplified response that does not consider the impact of load angle and AVR response on reactive power output. The real power (P) and reactive power (Q) from the machine is given by (5).

$$P + jQ = \frac{E \bullet V}{X}\sin\delta + j\left(\frac{E \bullet V}{X}\cos\delta - \frac{V^2}{X}\right) \quad (5)$$

Where E is the internal voltage magnitude, V is the terminal voltage magnitude, X is the generator reactance, and δ is load angle. When motoring occurs, δ ramps down to a small negative value. From (5), it is evident that P and Q are both affected. This, in turn, affects terminal voltage. The AVR reacts to bring voltage back to nominal, causing a further change in Q. The final value for Q depends on the details of the power system. Fig. 4 shows a simulated response of a machine to a motoring event with the AVR in Auto. In this simulation, a step in mechanical power from 0.85 to –0.005 was applied. Note that the terminal voltage undergoes a slight increase, and the reactive power undergoes a slight decrease.

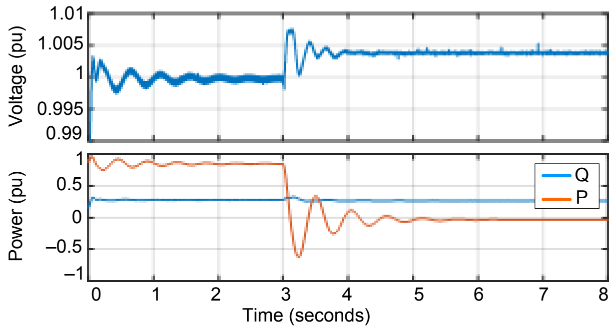

Fig. 4. Simulated motoring response.

3 Instrument transformer accuracy

In order to evaluate the possibility that the dependability of the reverse power element may be compromised, it is necessary to understand the nature of errors from the instrument transformers. In general, a CT or VT may be represented by the equivalent circuit of Fig. 5. The complex impedances $Z_P=R_P+jX_P$ and $Z_S=R_S+jX_S$ represent the resistance and leakage reactance of the primary and secondary windings. In this equivalent circuit, the primary impedance is reflected to the secondary side by the square of the turns ratio. The $R_E||jX_M$ branch of the circuit represents the magnetizing branch impedance. Z_B is the connected burden which includes secondary wiring, relays, and meters. The current (I_E) in the magnetizing branch is a nonlinear function of the saturation voltage (E_S) and is defined by the excitation curve.

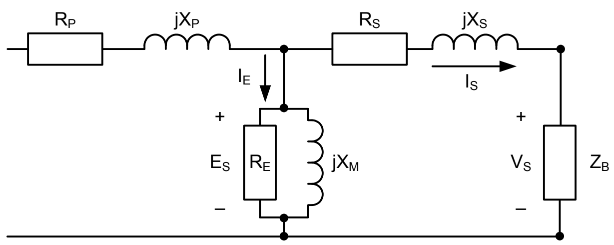

Fig. 5. Instrument transformer equivalent circuit.

In the case of a CT, the input to the circuit is an ideal current source with a value of I_P/CTR where I_P is the primary current, and CTR is the CT ratio. In a protection class CT, the primary impedance and secondary leakage reactance can be neglected. Fig. 6 shows the relationship between the primary, secondary, and excitation currents.

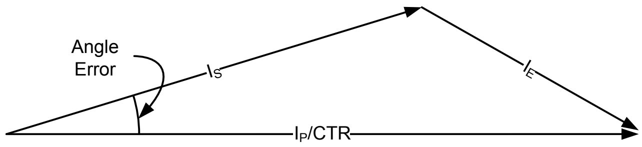

Fig. 6. CT relationships.

In the case of a VT, the input to the circuit is an ideal voltage source with a value of V_P/VTR where V_P is the primary voltage, and VTR is the VT ratio. The range of interest for the voltage is 90 to 110 percent of rated voltage. The primary source of error (ΔV) is the voltage drop across the winding impedance branches as shown in Fig. 7. It can be approximated using (6).

$$\Delta V \approx \frac{V_P}{VTR} \bullet \frac{Z_P + Z_S}{Z_P + Z_S + Z_B} \quad (6)$$

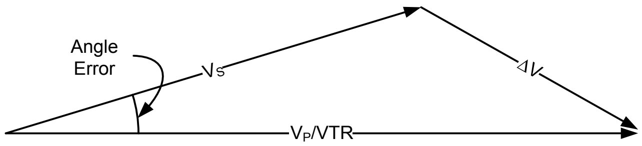

Fig. 7. VT relationships.

3.1 Industry standards

Examination of industry standards for instrument transformers used for protection and metering reveals that errors greater than 0.25 degree (15 minutes) can be expected in real world applications. Sections 3.1.1 and 3.1.2 summarize the relevant specifications.

3.1.1 ANSI accuracy specifications

For metering CTs, the American National Standards Institute (ANSI) specifies three accuracy classes (0.3, 0.6, and 1.2) and five standard burdens (0.1, 0.2, 0.5, 0.9, and 1.8 ohms) [4]. These specifications are given for a CT nominal secondary of 5 A and a frequency of 60 Hz. The standard burdens are inductive at a power factor of 0.9. For example, a CT with a nameplate label of 0.3B-0.5 has an accuracy class of 0.3 when connected to an impedance of 0.45 + 0.22j ohms. If the nominal secondary is a value other than 5 A, the impedance is multiplied by $(5/\text{nominal secondary})^2$. The limits for angle errors at the standard burden are given in Fig. 8. In Fig. 8 and Fig. 9, the Y axis is the ratio correction factor, which is a measure of the total error including both magnitude and angle errors. Note that the angle error limit for CTs is dependent on the accuracy class but also on the current.

IEEE C57.13 does not specify an angle error limit for protection CTs. However, the CT may be dual-rated. In this case, the CT nameplate lists a metering accuracy and a protection accuracy.

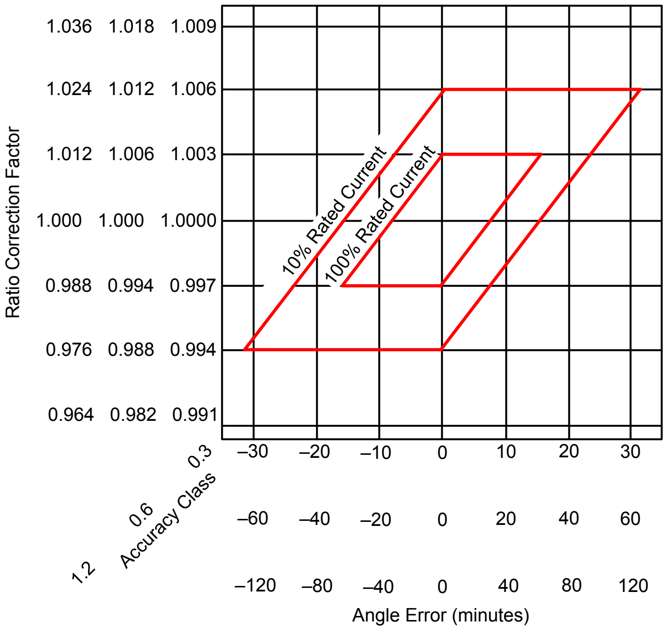

Fig. 8. Metering CT angle error limits (C57.13).

Metering VTs also have three accuracy classes (0.3, 0.6, and 1.2) and six standard burdens. Table 1 lists the burdens and their associated power factors.

Designation	Burden (VA)	Power factor
W	12.5	0.10
X	25	0.70
M	35	0.20
Y	75	0.85
Z	200	0.85
ZZ	400	0.85

Table 1: VT standard burdens (C57.13).

Fig. 9 shows the angle error limits for VTs at the standard burdens. The VTs must meet these limits for voltages between 90 to 110 percent of rated voltage.

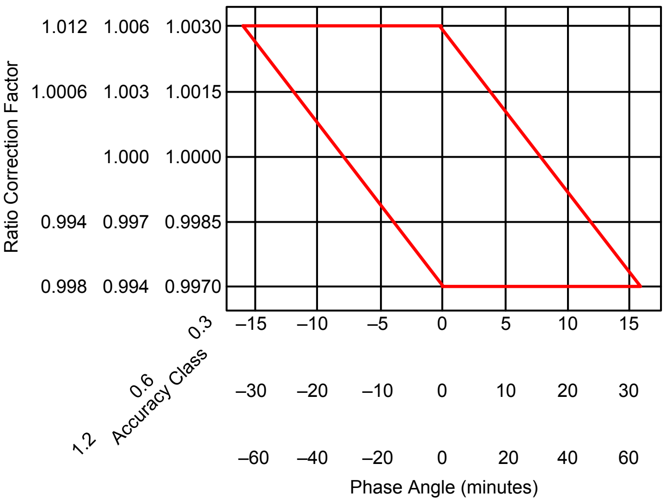

Fig. 9. Metering VT angle error limits (C57.13).

3.1.2 IEC accuracy specifications

The accuracy requirements for CTs are specified in IEC 61869-2 [5]. For Class P CTs, rated burdens of 2.5, 5.0, 10, 15, and 30 VA are specified. A power factor of 1 is specified at 2.5 VA. A power factor of 0.8 lagging is specified for all other burdens. A plot of angle error limit versus current is shown in Fig. 10.

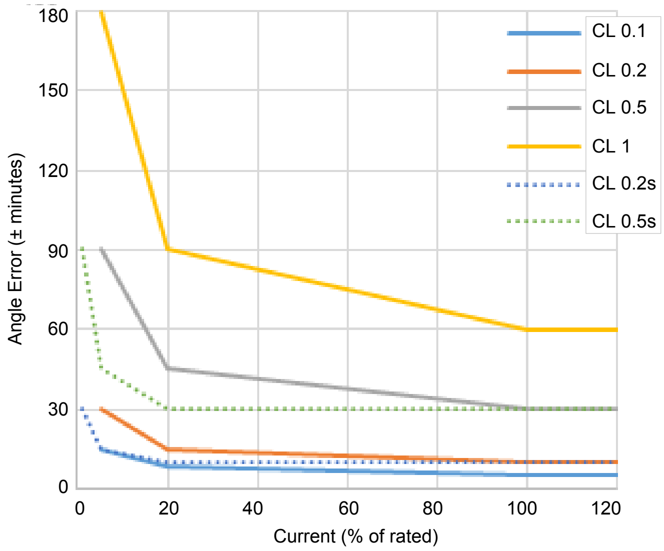

Fig. 10. Metering CT angle error limits (IEC 61869-2).

The standard also specifies Class 3 and Class 5 accuracy classes. However, angle error limits are not specified for these.

Accuracy limits are not specified above rated burden or below 25 percent of rated burden.

The angle error limits for protection CTs are given in Table 2.

Class	Angle error limit (minutes)
5P and 5PR	±60
10P and 10PR	Not specified

Table 2: Protection CT angle error limits (IEC 61869-2).

IEC 61869-3 specifies the accuracy requirements for VTs [6]. These are listed in Table 3 and Table 4.

The requirements are specified at rated frequency and for voltages ranging from 80 to 120 percent of rated voltage. The requirements are also specified for a range of 0 to 100 percent of rated burden for a power factor of 1; and 25 to 100 percent of rated burden for a lagging power factor of 0.8. Standard burdens are 25, 50, and 100 VA.

Class	Angle error limit (minutes)
0.1	±5
0.2	±10
0.5	±20
1.0	±40
3.0	Not specified

Table 3: Metering VT angle error limits (IEC 61869-3).

Class	Angle error limit (minutes)
3P	±120
6P	±240

Table 4: Protection VT angle error limits (IEC 61869-3).

3.2 Instrument transformer testing

Test sets are now available that allow angle errors to be measured to an accuracy of less than 3 minutes. These units run tests to determine the parameters to model CTs according to both ANSI and IEC standards. Table 5 shows the results from a CT test. The angle errors are reported at various levels of secondary current and connected burden.

Connected burden	Phase displacement in minutes at % rated current					
VA/PF	1	5	10	20	50	100
200 VA/0.5	2.63	0.83	0.42	0.21	0.06	0.04
100 VA/0.5	2.75	1.02	0.64	0.39	0.21	0.13
50 VA/0.5	2.80	1.11	0.77	0.52	0.31	0.22
25 VA/0.5	2.75	1.15	0.83	0.59	0.37	0.27

Table 5: Example CT test results.

3.3 Impact of connected burden

In general, manufacturers design instrument transformers to meet the previously described limits over a range of connected burdens which includes the rated burden. The lowest errors do not necessarily occur when the connected burden matches the rated burden (either in impedance or power factor). If accuracy measurements are available from the manufacturer at various burdens or if test data are available (see Section 3.2), the error for the actual connected burden can be estimated using the equivalent circuit shown in Fig. 5. However, this level of detail is often unavailable to the protection engineer.

Note that the transient performance of a CT during an external fault is also a function of connected burden. A lower connected burden produces a better transient performance. Therefore, the optimal burden for antimotoring may not be optimal for the balance of protection.

4 Dependability-biased characteristic

The new algorithm introduces a bias into the characteristic as shown in Fig. 11. The new characteristic modifies the reverse power tripping characteristic: instead of being at a fixed real power level at ±90 degrees on the PQ plane, it includes a small angle bias so that the farther from the origin on the PQ plane the operating point becomes (where the angle error has an effect), the more relaxed the reverse power threshold becomes. With the modified characteristic, the measured operating point with the error is still well inside the tripping characteristic and the antimotoring protection trips dependably. The bias angle should be greater than the largest expected angle error.

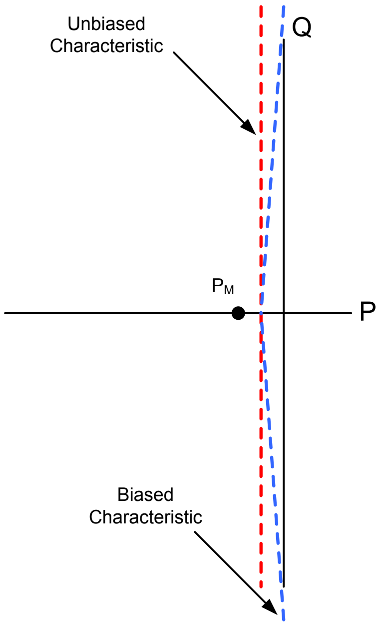

Fig. 11. Element characteristic.

There is no valid operating condition in which the machine would be operating at low forward power and high VAR output where the dependability bias would cause a misoperation during normal operation, except possibly immediately following synchronization. If the generator is synchronized to the system with a fairly large difference between the generator terminal voltage and the system voltage, the VAR flow upon initial synchronization could jump up quickly before the machine is loaded.

To address this condition, the element is adaptive. It starts out with the traditional fixed power threshold and then switches to the dependability-biased characteristic after a short delay. The logic works as follows. When the current is less than approximately 5 percent of generator rated current for approximately 60 seconds, the element switches to the unbiased characteristic. At low current magnitudes, any angle error has little effect and the dependability-biased characteristic is not required. Once the current is greater than 5 percent for approximately 60 seconds, the element switches to the biased characteristic.

This adaptive characteristic makes the element more secure when starting and more dependable when shutting down. The delays prevent the element from chattering during a power swing. The element characteristic is therefore dynamic, a feature which is becoming more common in digital protection designs. The state machine in Fig. 12 shows the scheme logic.

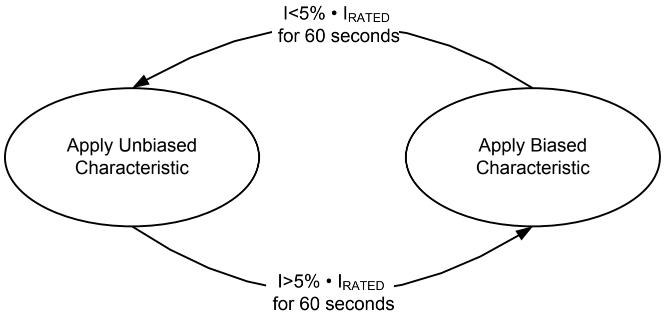

Fig. 12. Characteristic switching logic.

4.1 Comparison with low forward power

In the past, a low forward power scheme was applied in cases where the dependability of the reverse power element was marginal either because the relay is not sensitive at very low currents (as described in Section 1) or because of angle errors at near-zero power factor. In this scheme, the power pickup threshold is shifted to the right-hand side (positive P) of the PQ plane. The element is blocked when the generator is offline because P is zero. Also, the element removal of the block must be delayed following synchronization to allow enough time for the generator power output to be ramped above the pickup threshold of the power element. The advantage of the scheme is that the pickup of the power element can be moved far enough into the positive power region to ensure pickup during an actual inadvertent motoring event. The drawback of the scheme is its reliance on the breaker status to enable and disable the scheme. In addition, a separate reverse power element is also required for the sequential tripping scheme.

The new dependability-biased characteristic provides the same level of dependability without the need for breaker status. The same element can be used for sequential tripping and for detection of inadvertent motoring.

4.2 Application guidelines

The new characteristic is not required and the reverse power element can be set with a conventional characteristic for the following applications:

- Motoring power is high (greater than 5 percent).
- Motoring power is low, but the generator will not motor with significant VARs (sequential trip or exciter is always in power factor regulation mode).
- Motoring power is low, but the angle errors do not result in a loss of dependability, such as when metering transformers are used or when transformer accuracy has been measured and compensated for.

Otherwise, the element is enabled and the pickup threshold is selected according to typical guidelines (for example, ½ P_M). The default bias angle of the element is secure for motoring levels of less than 1 percent with a total angle error of up to 2 degrees.

5 Conclusion

This paper describes how dependability of the reverse power element in detecting an inadvertent motoring condition can be compromised on machines with low motoring power. It also presents a new algorithm with a dynamic operating characteristic. The concept can be categorized with other dynamic characteristics; for example, the memory-polarized mho which expands to provide better resistive coverage or the adaptive percent-differential which increases its slope during periods when CT saturation is more likely.

The new scheme is very simple to understand and use. The exact setting for the dependability-bias angle is not critical, so default settings can applied in most applications. The adaptive element introduces no significant reduction in the security of the protection. This element is recommended for use in all applications except those specifically excluded in Section 4.2 to reduce the possibility of failure to trip when the rare inadvertent motoring event occurs.

References

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20151118 • TP6737