BACK TO THE TABLE OF CONTENTS

Impact of Frequency Deviations on Protection Functions

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1. Introduction

The subject of response of protection function to frequency deviations gained interest among relay users and regulatory bodies in the light of the 2003 Blackout investigation and subsequent NERC activities.

This paper looks at performance of a wide variety of protection functions under abnormal system frequencies.

The paper focuses on both security and dependability under a number of events of interest combined with off-nominal frequency. The events of interest include internal and external faults, transformer inrush, line pickup and other traditionally considered protection events. The off-nominal frequency events focus on real-world scenarios that produce frequency deviations as well as stable and unstable power swings.

With reference to microprocessor-based relays the paper explains digital measurements under varying fundamental frequency, and reviews concepts of frequency compensation and frequency tracking. The paper also reviews practical methods used to measure frequency in microprocessor-based relays.

This tutorial paper provides insights into internal workings of typical microprocessor-based relays and educate protection engineers regarding possible responses of protection functions under dramatic frequency events in the power system.

2. Signal processing in a typical microprocessor-based relay

The typical microprocessor-based relay is comprised of the following major blocks:

Analog Input and electrical insulation: Analog input signals supplied from VTs and CTs are electrically isolated from the internal circuits of the relay by input transformers, reducing signals levels in order to make them suitable for use in the relay.

Analog low-pass filter: The analog anti-aliasing filter, is a low pass filter, with design constants determined by the sampling rate of the relay The low-pass filter is needed to reject high frequency components which can appear in the input signal and may affect relaying functions.

Sample and Hold: Typically a digital relay samples multiple input signals at 4 to 128 times per power cycle. The sample and hold circuit ensures that samples from each input are captured at the same instant. This is required since A/D conversion is usually carried out on each signal in sequence. Because the multiplexer scans the input signals sequentially, but signals have to be processed in parallel (to maintain phase relationship between each signal, there should be exactly same instance, when samples are captured from input signals.

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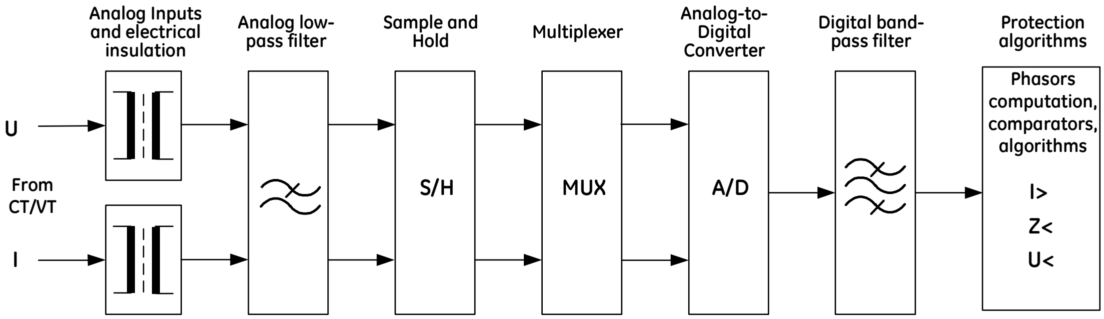


Figure 1. Signal Processing in the Typical Microprocessor-based Relay.

<u>Multiplexer</u>: The Multiplexer collects samples from each input and passes these sequentially to the Analog-to-Digital Converter.

<u>Analog-to-Digital Converter</u>: The values corresponding to the input variables which are now in the serial form are quantized into serial discrete signals by the A/D converter.

<u>Digital band-pass filter</u>: The element of primary interest in the power system signal is its fundamental frequency component. However, harmonic components and non-harmonic components are present in the signal due to non-linearities of the system and transients produced during the disturbance. Filtering is required to pre-process the signal in order to reduce effect of these components prior to phasor estimation.

<u>Protection algorithms</u>: There are several phasor estimation techniques used for protective relaying purposes, such as the Discrete Fourier Transform, Cosine algorithm, Least Squares algorithm, Kalman filter and Wavelet transform. Most of the relays are using either the Discrete Fourier Transform or Cosine algorithm. Once signal phasors are estimated, protection algorithms are executed.

All of these processes are controlled by the CPU. The CPU dictates the sampling frequency, which is derived from the measured system frequency. The sampling frequency must be an integer multiple of the system frequency in order to fit the intended number of samples into one power cycle. If, for example the relay samples at 64 times per cycle in a 60 Hz system, (i.e. 3840 Hz sampling frequency), but the system frequency is not 60 Hz, then the relay would not fit 64 samples into one cycle window and an error in phasor estimation would occur. To prevent this, relays either track the frequency to adjust sampling rate to the changing system frequency or compensate for off-nominal frequency when estimating the phasors.

3. Impact of frequency on phasor measurements

Microprocessor-based relays are typically designed to measure fundamental frequency components in their input signals for their short circuit protection functions. Frequency excursions are among severe system conditions. When the fundamental frequency of the power system changes, protective relays that use phasors adapt their estimation algorithms to retain accuracy. This is not a weakness of digital relaying, but advantage compared with analog schemes.

Straightforward phasor estimation algorithms such as the generic Fourier algorithm work well at the nominal system frequency. If the frequency changes, the measurement becomes less accurate in a manner similar to the measuring circuits of analog relays.

Figure 2 below illustrates this phenomenon by showing the frequency response of the cosine (real part of the phasor) and sine (imaginary part) filters that constitute the full-cycle Fourier phasor estimator. Working with the nominal frequency, the two filters have a unity gain yielding an accurate phasor response.

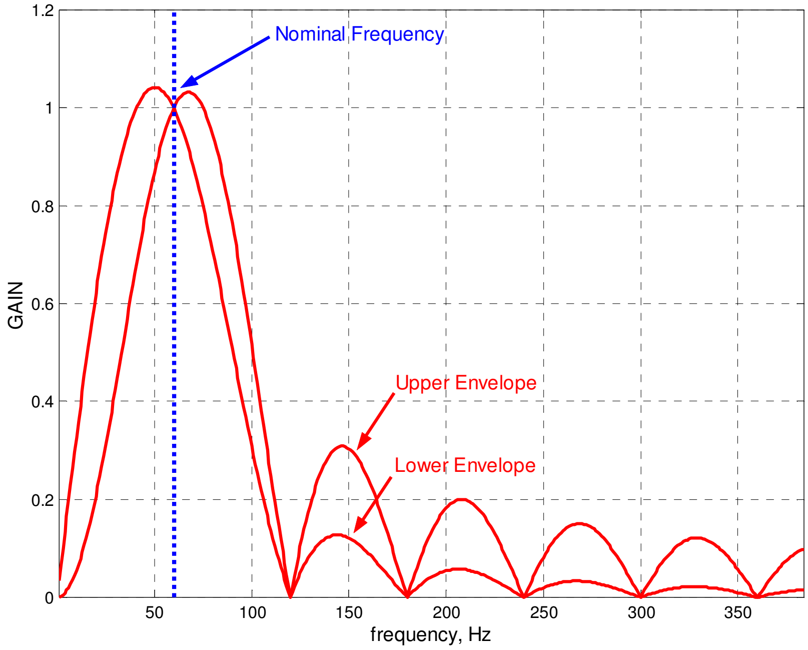


Figure 2. Frequency response of the full-cycle Fourier phasor estimator.

When at off-nominal frequency (Figure 3), the two filters display different gains yielding a phasor estimate with a superimposed ripple, and the average value becomes inaccurate. The exact nature of the error depends on the specific phasor estimation algorithm used.

To remain accurate under off-nominal frequency conditions microprocessor-based relays either apply a variable sampling frequency scheme (frequency tracking), or apply a constant sampling frequency but compensate the measured phasors mathematically for the difference between the nominal and actual system frequencies (frequency compensation). Both methods although implemented differently are quite similar: they measure the actual system frequency and adjust either the sampling clock, or the raw phasor measurements for the difference in frequency.

The adjustments for off-nominal frequencies are typically slow as the system frequency rate of change is limited by the system inertia. Often, various inhibiting or security conditions are implemented to prevent erroneous frequency measurements *under faults and other abnormal conditions that could lead to anomalies in signal phase.*

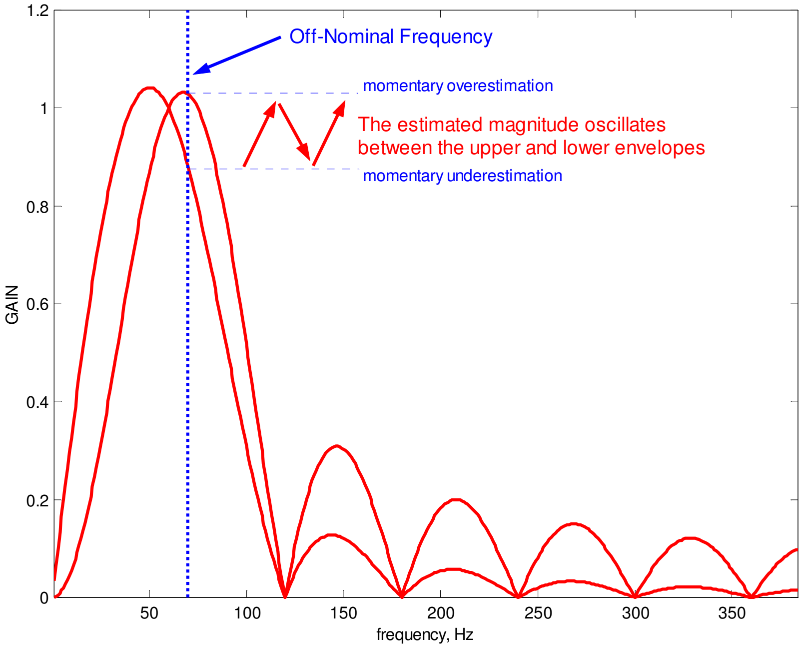


Figure 3. Full-cycle Fourier phasor estimator under off-nominal frequency.

Under stressed system conditions, the various implementations of the frequency tracking/compensating schemes may respond differently. In particular under a large rate of change of frequency some implementations may either refuse to track, or lag considerably the actual and fast changing system frequency. Some implementations may stop tracking at certain upper or lower limits.

In a simple case of straight current differential function implemented on a per-phase basis, errors in phasors due to off-nominal frequencies are not consequential. Assuming all currents of a differential zone are measured using the same, even though not correct sampling frequency, the resulting differential signal will zero-out as long as the instantaneous signals balance to zero. The phasor estimate is mathematically a linear operation: if the instantaneous signals balance, their phasors would balance as well regardless of the off-nominal frequency errors, or transient errors.

The above optimistic observation does not apply to harmonics used for inrush or overexcitation inhibit, or to mixed-mode differential functions. Also, if some of the currents are measured using different frequency tracking, extra errors will be created. The following sections elaborate on these effects.

4. Impact of frequency deviation on relay operating signals

The magnitude of the error produced by a frequency deviation depends on the relay design, particularly the filtering and phasor estimation technique. Also, errors in the voltage and current channels may be quite different due to different pre-filtering *method employed. The off-nominal frequency (difference between the signal and relay tracking frequencies) has an effect on the digitally measured magnitudes and angles. The magnitudes start to show a characteristic ripple effect as illustrated for the phase voltages in Figure 4 below.*

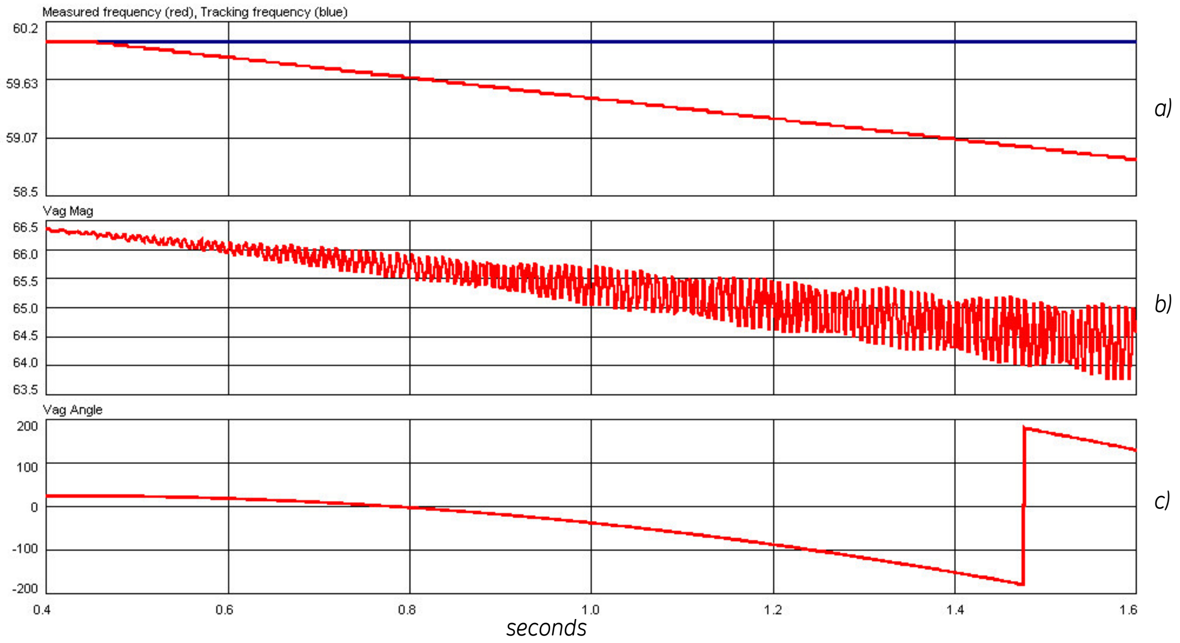


Figure 4. Relay record. Effect of the off-nominal frequency on the magnitude and angle measurement with frequency tracking disabled; a) system frequency (red), tracking frequency (blue), b) magnitude of VA, c) angle of VA

The angles will shift at a speed proportional to the differences between the two frequencies. For example, if the two frequencies differ by 7 Hz, the angles will shift at 7 times / sec x 360 deg = 2520 deg / sec, or 252 deg every 100 msec, or 42 deg every power system cycle. If the difference between the signal frequency and tracking frequency increases proportionally with the square of time, the angles will change proportionally to the third order of time. If the difference between the signal and tracking frequency increases linearly, the angles will also change linearly as illustrated in Figure 4 for the phase A voltage.

As seen in the Figures 4 and 5, the amount of ripple (peak-to-peak magnitude) is approximately proportional to the frequency error, assuming relatively small frequency deviation of few Hertz. Depending on the actual estimator used, the error can be both positive or negative as in the case of straight Fourier algorithm or may be slightly asymmetrical, i.e. biased more towards underestimation rather than overestimation.

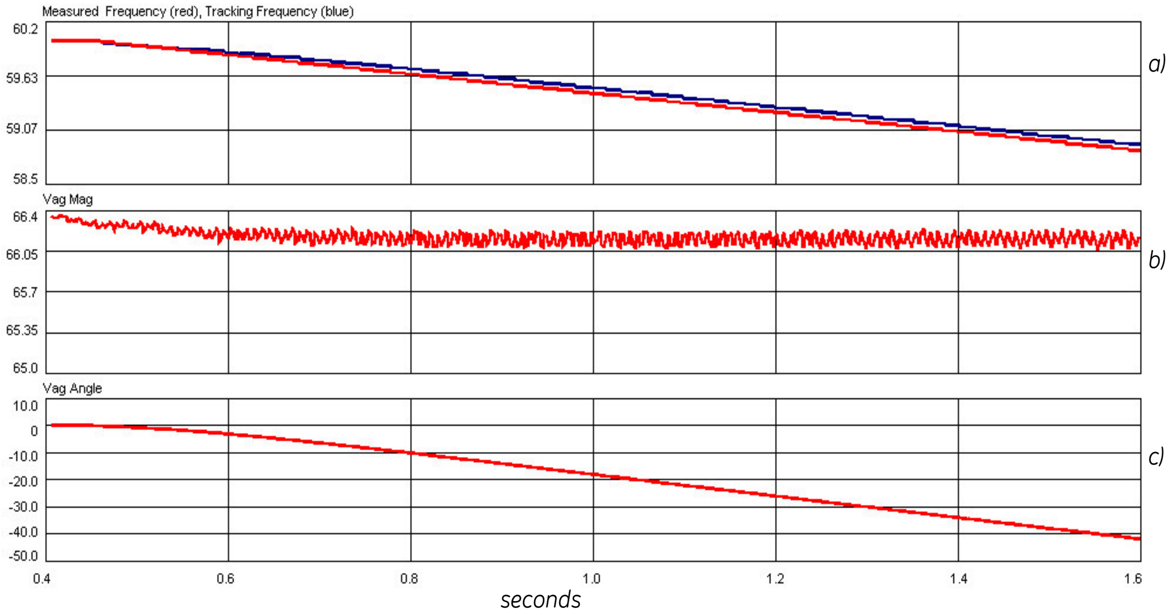


Figure 5. Relay record. Effect of the off-nominal frequency on the magnitude and angle measurement with frequency tracking enabled; a) system frequency (red), tracking frequency (blue), b) magnitude of VA, c) angle of VA

It should be noted that during conditions described above, the angular relationships between voltage phases and current phases are maintained, therefore sequence components are calculated properly but magnitude and angle are affected same way as phase quantities. Consequently, it means that if relay is tracking the system frequency closely and is using actual measured voltage and current quantities for protection algorithms, it will experience excessive error in magnitude and angle estimation as explained above. If, however, relay is using some historic value for current and voltages, such as memory voltage in the case of distance and directional elements, it may be prone to misoperation.

5. Impact of frequency on typical relay comparators

Microprocessor based relays typically incorporate various security measures to ensure reliable operation. Although the relay may sample the input signals as often as 128 times per power cycle, the execution of the protection algorithms (known as a protection pass) is carried out less often, typically at 4 to 16 times per cycle. This is done in order to reduce loading on the CPU and DSP and to reduce data transfer rates between the DSP and CPU thereby realizing the required speed of operation. At each protection pass, in addition to running protection algorithms, the relay executes programmable logic, evaluates input/output states, refreshes metering data, etc. To avoid nuisance operation due to transients and noise, the protection function is allowed to issue a trip command only if element's comparators are satisfied for a fixed number of consecutive protection passes (typically 1-5). The process of requiring comparator operation for multiple protection passes is usually referred as adding "security counts". Depending on the vulnerability of the element to transients and noise, and the required operating speed a different number of security counts may be chosen at the design stage. Despite the fact that relay operation is actually delayed, the security counts process has a positive impact on the elements operation during off-nominal conditions. A protection element may not be able to satisfy its security counts because of oscillation of the phasor magnitudes, causes comparators to pickup and reset during consecutive protection passes.

6. Types of frequency-related events

A. Transmission System Load/Generation Mismatch

Under normal operation a good match generally exists between generation and load within the power system. This balance is upset for the loss of a large load or generator or when part of the grid becomes islanded. During such an event, synchronous machines will release or store kinetic energy in their rotors – changing speed accordingly. For a system comprised of a single machine connected to a load, the acceleration of the rotor can be expressed as follows:

$$\frac{d\omega_r}{dt} = \frac{1}{2H} \cdot \left(T_e - T_m\right) \qquad (1)$$

where T_e and T_m are the electrical and mechanical torques, ω_r is the rotor radian frequency, and H is the inertia constant of the machine. Integration of this expression results in an expression for frequency that varies linearly with time. It is also evident that frequency varies directly with mismatch and inversely with inertia. In a practical power system the variation in frequency may not be linear due the influence of generator controls, the action of load shedding schemes, and the frequency dependant nature of some loads. Such an event may be recoverable or may result in system collapse in extreme circumstances.

B. Power Swing

A power swing can be described as a change in power flow between two points in the power system. A power swing can occur as a result of a fault in the network. The fault followed by the subsequent opening and reclosing of circuit breakers changes the impedance between machines at different points in the system. The power transferred between these points is given by the well-known equation:

$$P_e = \frac{|V_A| \cdot |V_B|}{X} \cdot \sin(\delta) \qquad (2)$$

Due to the mismatch between P_e and P_m, a machine connected at either terminal machines will accelerate and/or decelerate as a result of the change in the interconnecting impedance.

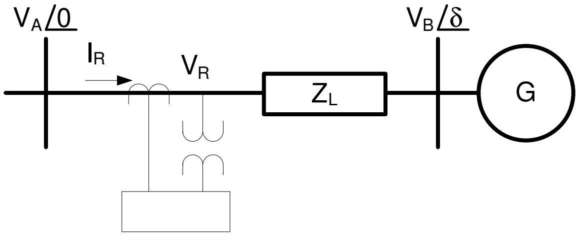


Figure 6.Illustration of the swing phenomenon

Therefore a power swing will be accompanied by a changing frequency. At a given terminal the frequency of the voltage V_R seen by the relay is a functions of the voltage at that terminal (which could be changing) and the frequency of the current I_R is a function of the voltage at both terminals.

C. Generator Rejection

When a loaded generator is disconnected from the system, the electrical power P_e is immediately forced to practically zero (neglecting any local auxiliary loads) and the machine will accelerate according to equation (1). Many machines are not designed to ride through such an event and will be shut down by automatic controls. Other machines may be required to remain in operation in order to facilitate reconnection to the system. These machines will overspeed until the governor can bring the speed back to its nominal value. The frequency will respond in-kind. Hydro machines in particular can exhibit significant overspeed due to the delayed governor response. During such events the voltage can also undergo a significant increase and decrease.

D. Generator Static Starting

A modern gas turbine is often started as a synchronous motor connected to a load commutated inverter (LCI) – a method known as static starting. The frequency and voltage are ramped from zero to rated values in concert to avoid overexcitation of the stator. During this process a subset of the generator protections remain in-service. These protections are exposed to a wide range of frequency.

E. Motor Bus Transfer

In an industrial plant or a generating station, busses feeding critical motor loads are often supplied by multiple sources. Only one source will normally supply the bus in order to limit the available short circuit currents. If the source is lost, automatic controls will transfer the bus to the healthy source. During this transfer, the motors will maintain the voltage on the bus. The frequency (and magnitude) of this voltage will decay as the machines coast down. Depending on the type of transfer scheme the deviation in frequency from its nominal value can be significant.

F. Transmission Line Voltage Ring-Down

When one or more phases in a transmission line are isolated from the power system the frequency of the voltage on those phases is no longer determined by the power system frequency. If the line has shunt reactors, the isolated circuit will have a natural response that is dictated by the resonance between these reactors and the shunt capacitance of the transmission line. This resonant frequency can be significantly different from the nominal frequency of the power system. Depending on its design, a relay that is fed from the line CVT could track to the resonant frequency while the breaker is open. The relay will then have to respond to an instantaneous change in frequency when the breaker closes.

7. Dependability and security of major protection functions in microprocessor-based relay

From the preceding considerations it may seem that microprocessor-based differential relays are exposed to a variety of problems during off-nominal frequencies. The reality is that these relays support frequency tracking / compensation and by the virtue of it are actually less prone to the problem compared with analog relays. The situation of off-nominal frequency must be understood as a period when the relay frequency tracking mechanism is lagging the actual system frequency. Once the relay has measured the frequency accurately, it regains its theoretical precision even though the system frequency is not nominal. As a result, the off-nominal frequency issues occur practically only during fast frequency changes when the relay may apply security averaging and as a result adjust tracking frequency intentionally slower than the changes in the power system. For example some of the islands during the 2003 blackout showed frequency changes in excess of 30Hz/sec for a duration of 100-200ms during system break up. Some relays did not allow such rapid changes in their tracking frequency, which led to a temporary lag between the system and tracking frequencies. Normally, even during severe system events, the frequency changes well within the design limits of the relay frequency tracking / compensation mechanism allowing it to catch up to the system frequency and maintain correct measurements. It is only during moments where frequency changes fast enough to disable frequency tracking, or during the absence of the signal selected for tracking, that the problems described here occur.

In contrast, analog relays respond continuously throughout disturbances in a deteriorated, difficult to predict way under off-nominal frequencies as dictated by the design limitations inherent with their electro-mechanical and solid-state technology

7.1. Instantaneous phase overcurrent protection

Depending on the filtering design of the currents, uncompensated relay may exhibit an error of 1%/Hz-2% per Hertz. In generator static starting applications, uncompensated overcurrent relays can significantly underestimate the current at very low frequencies.

7.2. Time-delayed phase overcurrent protection

Likely is less affected than instantaneous elements due to fluctuation of the phasor magnitude; values below comparator limit would reset element. This may depend on the relay design, however.

7.3. Voltage protection

A voltage element that responds to the phasor magnitude and does not employ frequency compensation will underestimate the voltage as was illustrated in Figure 3. In generator applications an overvoltage element may fail to operate at its setting value during an overspeed condition. In a motor bus transfer application an undervoltage element may pickup at a higher value than it's setting value; thereby transferring the bus at a voltage that is higher than permissible

7.4. Directional protection

An uncompensated directional elements would experience errors in its voltage and current angle measurements. These errors would likely cancel out to a large extent. Some phase directional elements employ memory polarization to ensure correct operation during a close-in fault. A significant error could develop between the angle of the memorized voltage and the true value during off-nominal frequency operation. This could result in loss of directionality. The situation is similar to that encountered with distance elements (see section 7.8).

7.5. Bus differential protection

Low impedance differential schemes, particularly bus differential functions, may incorporate countermeasures to the CT saturation problem. One such method tracks the trajectory of the differential-restraining point during faults and other events in order to differentiate between internal faults and external faults that may lead to CT saturation and potential security problems. With reference to Figure 7, the external fault trajectory would move to the right reflecting the elevated through fault current, before any CT saturates to produce a spurious differential signal and move the trajectory up towards the slope line and potential misoperation. During internal faults, the differential signal does not lag the restraining signal, but develops simultaneously. The difference between the two distinct trajectories allows the detection of external faults to block or enable extra security measures to improve immunity to CT saturation.

Note that during power swing conditions the restraining current will also become elevated, but with no differential current following the changes in the restraining signal. This may trigger the CT saturation detection algorithms in a differential relay, and bias it towards security.

As a result the ability to trip internal faults during, or just after, a power swing may become questionable. The unblocking action is generated based on various conditions using proprietary approaches, and its response is difficult to generalize without the knowledge of the inner workings of a given relay.

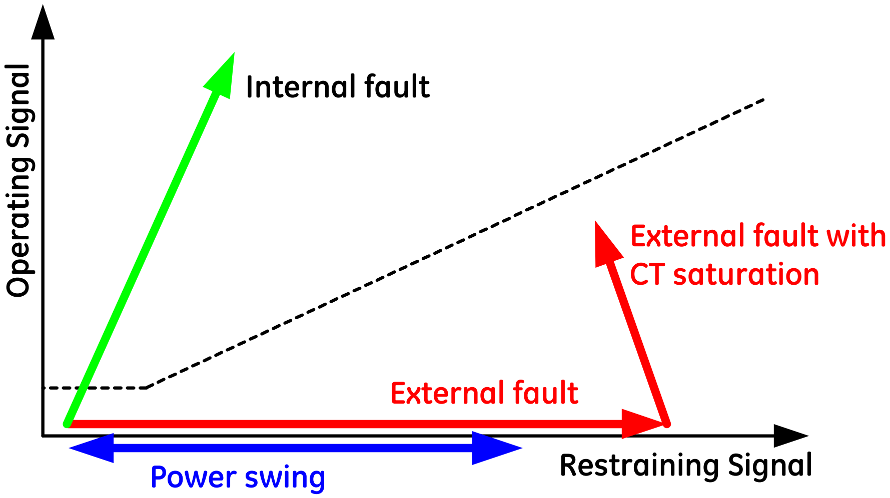


Figure 7. Illustration of CT saturation detection method.

7.6. Transformer differential protection

In the case of the transformer differential function the core balance equation combines both Kirchhoff's equations for the currents, and magnetic balance equations for the transformers core. The second harmonic inhibit is typically used to provide security during transformer magnetizing inrush conditions; while the fifth harmonic inhibit is used to ensure stability of the differential function during stationary core overexcitation conditions. Often, extra security means are implemented to deal with saturation of current transformers. Traditionally transformer differential relays use second and fifth harmonics to inhibit on magnetizing inrush, and stationary overexcitation, respectively.

Under extreme system events transformers may be exposed to multiple cases of inrush (fault recovery inrush, out of step breaker closure) and overexcitation (elevated voltages, low frequency). The ability to restrain correctly under such conditions is important to limit cascading tripping during major system disturbances.

During off-nominal system frequencies, the harmonics that signify inrush or overexcitation move following the frequency of the fundamental component. When the fundamental frequency changes by 1Hz, the position of the second harmonic changes by 2Hz, and the fifth harmonic – by 5Hz. A transformer relay must compensate for this *phenomenon, or else both security and dependability problems could occur. Figures 8 and 9 illustrate this effect by showing frequency response of sample second and fifth harmonic filters under nominal and off-nominal frequencies, respectively.*

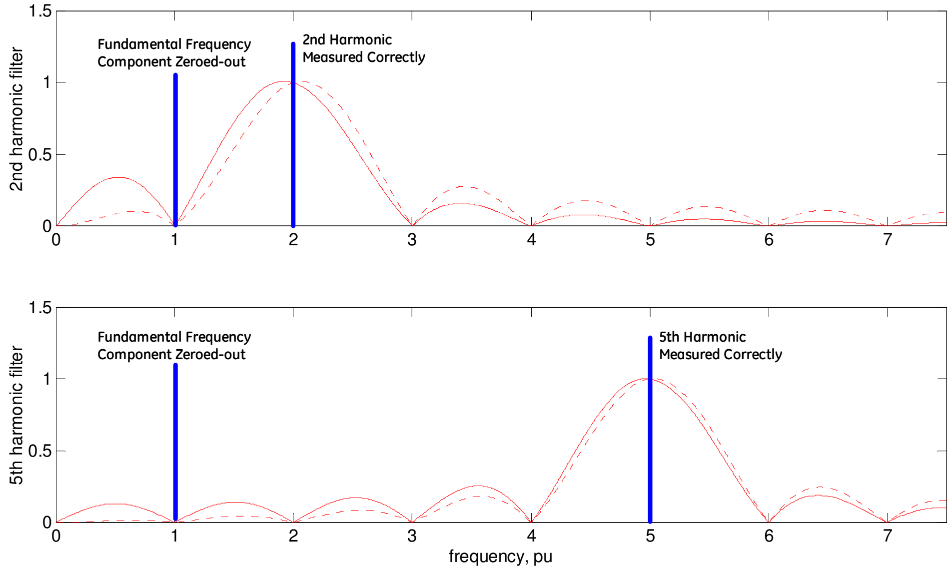


Figure 8. Illustration of 2nd and 5th harmonic measurements under nominal system frequency (full-cycle Fourier)

Two effects take place. First, when perfectly tuned to the actual harmonic, the filters remove entirely the dominating fundamental frequency component (zero gain). Under off-nominal frequencies, some portion of the large fundamental frequency component will leak in to the comparatively small value harmonic measurement, and depending on whether the leakage reinforces or opposes the harmonic, can result in gross under or over-estimation of the harmonic content. Given the relatively low inhibit thresholds, over-estimation leads to a problem with dependability of protection should an internal transformer fault occur in response to severe system events (e.g. elevated and long lasting power swing through currents). Second, the harmonic filters may underestimate the actual harmonic levels under off-nominal frequencies should inrush or overexcitation actually take place. This may lead to deterioration in protection security.

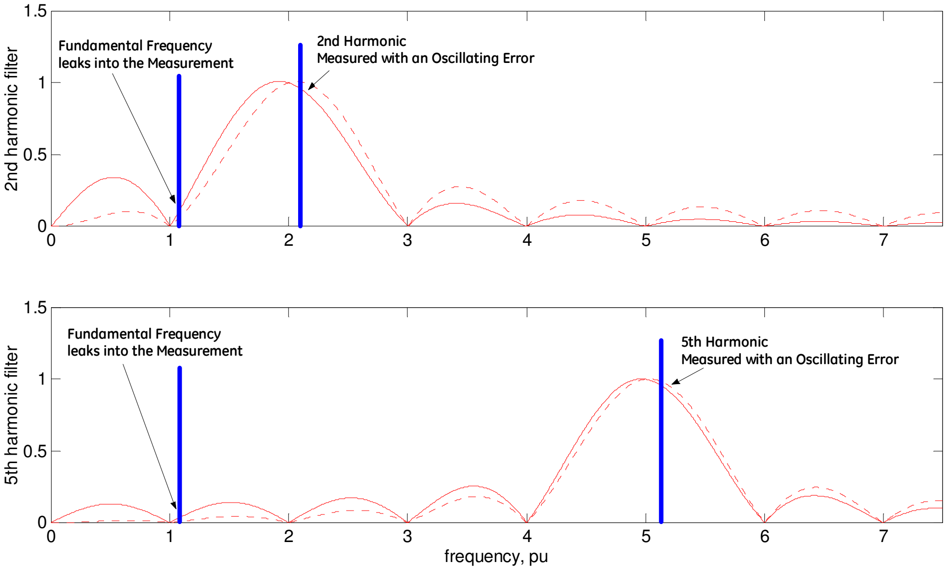


Figure 9. Illustration of 2nd and 5th harmonic measurements under off-nominal system frequency (full-cycle Fourier).

It should be noticed that the errors in harmonic measurements explained above are typically oscillatory in nature. This means a delayed operation is more likely to happen than non-operation (although the exact behavior is subject to details of inner workings of a given relay).

Security of protection may be truly impacted though. With multiple reclose operations potentially leading to magnetizing / sympathetic inrush, prolonged overexcitation conditions, power swings, etc. inaccurate harmonic measurements may jeopardize security of transformer protection

7.7. Line current differential

Microprocessor-based line current differential schemes sample their input signals at the individual terminals with two goals: first, to take the measurements at the same or precisely known points in time so that the digital measurements taken tens or hundreds of miles apart can be used in the same differential equations; second, to take the measurements in accordance for the actual system frequency. In other words the relays must stay in synchronism with each other, or with an arbitrary master to satisfy the differential protection principle in the first place, and should stay in synchronism with the power system for accurate phasor measurements.

With respect to the latter, a line current differential system may track the system frequency in either a symmetrical or asymmetrical manner. A symmetrical scheme uses an equivalent average frequency between all line terminals to adjust the sampling process or compensate the raw phasors. An asymmetrical scheme uses only local frequency measurement at a given terminal to adjust phasors taken at this terminal.

The symmetrical schemes are immune to off-nominal frequency problems. Even if the tracking/compensating frequency is not correct, its value is identical at all terminals of the line. Because all relays use the same tracking frequency, potential errors cancel as explained in the previous section, and no spurious differential signal is created as a result of off-nominal frequencies.

This is not the case for asymmetrical schemes. If each terminal uses frequency derived locally, the tracking frequencies may differ considerably between the terminals under severe system events. This is not necessarily because the actual system frequencies differ significantly, but because individual relays of the differential scheme may respond differently to their local input signals, for example different voltages when tracking frequency from the voltage signals. When the individual currents of the scheme are measured assuming different frequencies, spurious differential signals can be created jeopardizing security of the line current differential scheme.

Operation according to either the phase-segregated or mixed-mode principles is another important factor regarding off-nominal frequency performance.

Phase-segregated differential schemes are immune to errors caused by off-nominal frequencies as explained above. The mixed-current schemes may be exposed to some problems as follows.

The mixed-mode schemes are typically based on zero-sequence currents to cover ground faults, and negative-sequence currents for phase faults. The zero-sequence current if balanced under off-nominal frequencies between the line terminals, it will remain balanced as measured via phasors as well. However, spurious negative-sequence currents will occur in response to off-nominal frequencies. This may jeopardize security of the line differential scheme, unless the problem is recognized by the relay designers and extra measures are applied to counterbalance the phenomenon. Such measures in turn, often proprietary, might have unforeseen side effects on both security and dependability

7.8. Distance protection

The fact that distance relays employ memory voltage for polarization makes them quite vulnerable to misoperation. During a system disturbance leading to an off-nominal frequency condition, the pre-disturbance system voltage, which was likely at nominal frequency, may be memorized. Since phase comparator operating signal (IZ-V) is calculated from the current and voltage phasors a changing system frequency will cause this operating signal to rotate with respect to the memory voltage, which is stationary.

Memory-polarization uses pre-fault voltage as an indication of the emf force, driving the fault current. This assumption may not be valid in series-compensated line applications and in other special cases such as fast power swings.

Memory polarization results in expansion of the mho circle as driven by the equivalent impedance of the local system behind the relay. This is a positive effect when considering resistive coverage for close in faults, but a negative effect when *considering line loadability and impact of off-nominal frequency such as power swings on the underreaching directly tripping zone 1.*

When applying memory polarization several design aspects of the relay need to be checked. In particular:

a. *Security conditions to establish (validate) the memory before it could be used.*
b. *Triggering conditions to "freeze" the memory and start using it.*
c. *Security condition to abandon the memory and switch back to self- or cross-polarized modes before the too-old memory becomes inaccurate and causes problems.*

The memory duration timer must not be set too long – the system would respond dynamically to faults and other events by rotating slowly phasors at the relay point. The memorized value – in contrast – is a constant value. A combination of slowly changing phasor angles and static polarizing quantity would lead to a misoperation. Normally it is sufficient to set the memory duration timer longer than the longest breaker fail trip time for faults behind the relay. The latter time is the longest possible duration of a reverse fault under reasonable contingency scenario.

When the memory triggers, a constant value (angle) is used for polarization. Under fast swing conditions, the voltage and current phasors rotate at the rate dictated by the swing, and possibly the response of the frequency tracking mechanism. Assume the frequency tracking is relatively slow or disabled. Changing frequency or a swing would rotate the phasors at x degrees per cycle. If the memory is in place for y cycles, the total rotation (x deg/cycle times y cycles) may be large enough to align the IZ-V term with the Vpol and cause a spurious pickup of the mho comparator.

Therefore, under swings that exceed the frequency tracking capacity of a given relay, the memory circuit shall be forced to switch to the self-polarized mode.

Depending on the relay design, relay will track the frequency faster or slower. Major system events such as 2003 blackout demonstrated how fast frequency can change. With rates larger than 10Hz/sec, the frequency tracking mechanism may lag the actual frequency causing off-nominal frequency errors proportional to the difference between the tracking and actual system frequencies.

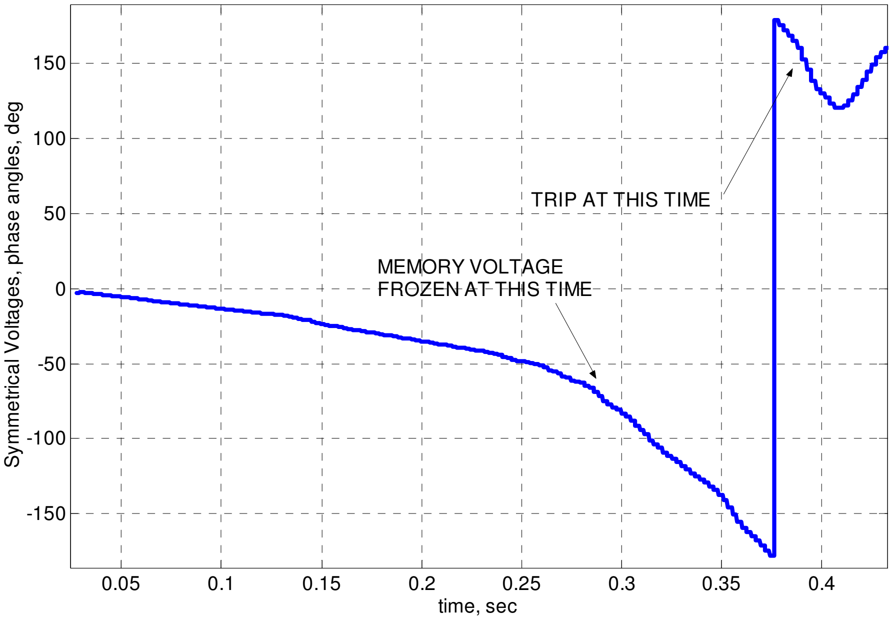


Figure 10. Angle of the Positive-Sequence Voltage.

Figure 10 demonstrates a relay operation during 2003 blackout due to memory positive sequence voltage was kept too long during a fast swing. Despite of the fact that the apparent impedance was far from zone of operation, as seen in Figure 11 below, the relay initiated a trip.

At the moment of tripping (t = 0.4 sec):

VAB = 26.7V, 162 deg

IAB = 0.605A, -82 deg

Z (Z1 reach setting) = 18.75 ohm, 87 deg

*Z*IAB - VAB = 37.4V, -11 deg*

Polarizing Voltage (memory) = 53.1V, -62 deg

Comparator angle = abs(-11-(-62)) = 51 < 90 deg – and the mho function operates.

This phenomenon could have been prevented if the relay was self-polarized at the moment of tripping (it switched to self-polarized at 0.465 sec). Assuming that polarizing voltage is the actual voltage at t = 0.4 sec, V1 = 15V, 150deg. The comparator angle would be abs(-11-(150)) = 161 > 90 deg, and the mho function would restrain.

This phenomenon does not depend much on the zone reach. For example, assume the reach was 1 ohm instead of 18.75 ohms, the IZ-V value would be 27.2V, -17 deg, and the mho function would operate as for the 18.75 ohm reach.

The relay would not operate if the memory duration setting was set lower. Let us analyze the operation of the memory-polarized mho function at t = 0.35sec.

VAB = 62V, -105 deg

IAB = 2.2A, -37 deg

*Z*IAB - VAB = 100.9V, 65 deg*

Polarizing Voltage (memory) = 53.1V, -62 deg

Comparator angle = abs(65-(-62)) = 127 > 90 deg – and the mho function restrains.

The apparent impedance was located at about 25-j28 ohms secondary at the moment of the relay operation. When the voltage started collapsing the relay saw the impedances moving towards the third quadrant with negative resistance. When the breaker opened, the impedances were located at about 5-j35 ohms secondary

With the memory duration of (0.35sec – 0.28sec) = 0.07sec or about 4 cycles the relay would have been fine. This is logical as the departure of the rotating vectors from their frozen position used for memory polarization is a function of elapsed time. With 10 cycle memory duration setting the frequency difference will have to be smaller; or with frequency difference of 7 Hz, the memory duration will have to be shorter.

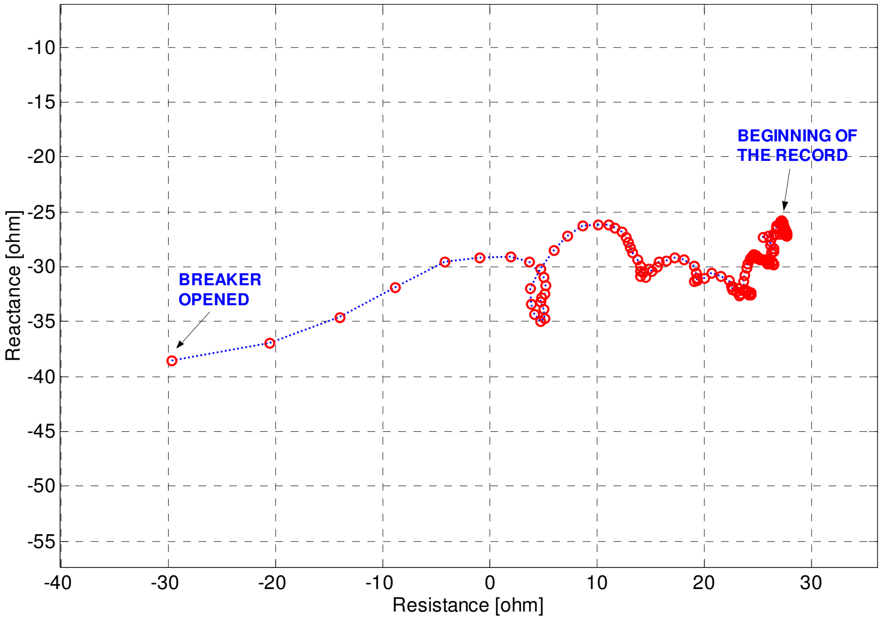


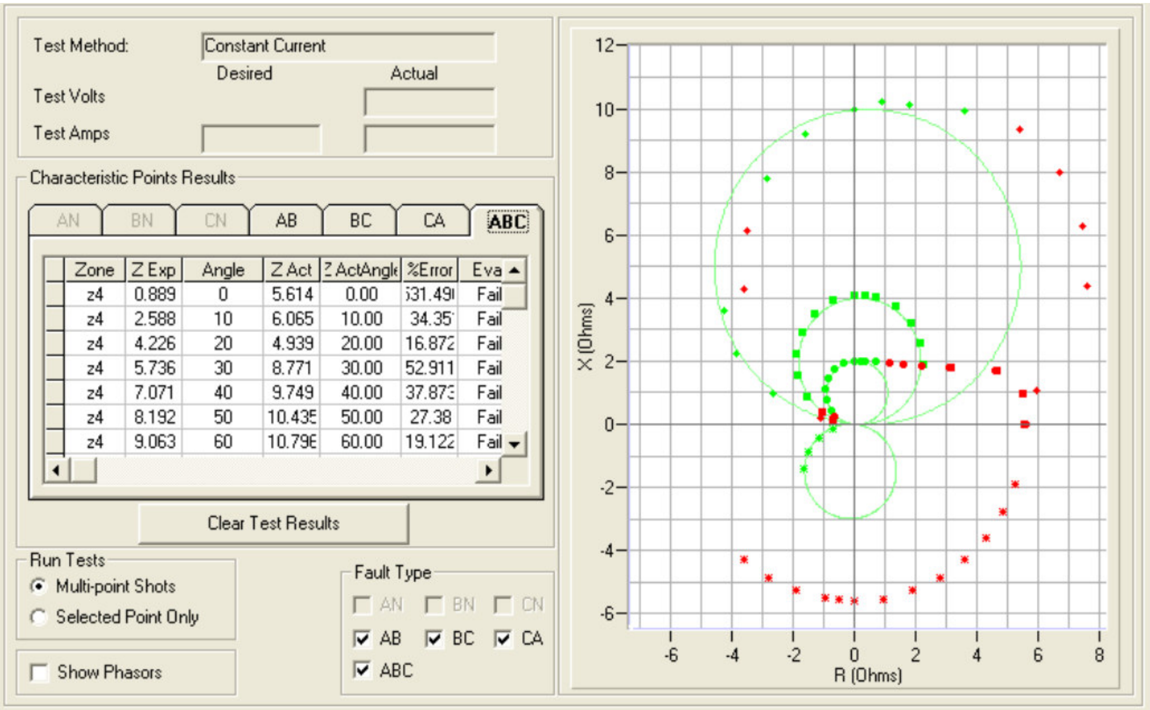
Figure 11. Impedance Trajectory – Positive Sequence.

The ground distance functions are immune to this effect because their overcurrent supervision responds to the zero-sequence current, and the latter is zero under balanced conditions.

8. Testing for impact of frequency deviations

It is important to check how well relay can cope with off-nominal conditions. The following steps can be considered to test relay operations:

- *Examination of the relay's frequency tracking mechanism per manufacturer literature and specifications to evaluate impact on the relays performance*
- *Measurement of the highest and lowest frequency for which the relay can measure/track/compensate to determine if it meets application requirements.*
- *Frequency ramp up and ramp down tests at different frequency rate of change, for example 0.1Hz/sec, 0.5Hz/sec, 1Hz/sec, 3Hz/sec, 5Hz/sec, 10Hz/sec with measurement of the of voltage and current phasors error.*
- *Step change in the frequency, for example 0.1Hz, 0.5Hz, 1Hz, 2Hz to determine how quickly and accurately that the relay can adjust its sampling frequency to match the system frequency-this may dictate necessary elements delays.*
- *Measurement of phasor errors during off-nominal frequencies such as power swings, sub-synchronous oscillations, harmonics, electrical noise.*
- *Measurement and estimation of various elements of interest impact during off-nominal frequencies conditions.*
- *Evaluation of distance and directional elements memory voltage functionality; memory voltage delays, ways to reset memory voltage, to force self-polarization. For example, if significant frequency change is detected (detected by underfrequency/overfrequency elements), or frequency is changing at the high rate (frequency rate of change element), then distance has to be become self-polarized in order to avoid nuisance operation The figure below demonstrates a test result for the forward looking instantaneous phase distance zone 1 testing at 58Hz, while tracking frequency is at 60Hz. Both the reach and element operating time were significantly impacted by this off-nominal frequency condition.*



Test Method: Constant Current

Desired Actual

Test Volts

Test Amps

Characteristic Points Results

Zone	Z Exp	Angle	Z Act	Z ActAngle	%Error	Eva
z4	0.889	0	5.614	0.00	531.49	Fail
z4	2.588	10	6.065	10.00	34.35	Fail
z4	4.226	20	4.939	20.00	16.872	Fail
z4	5.736	30	8.771	30.00	52.911	Fail
z4	7.071	40	9.749	40.00	37.873	Fail
z4	8.192	50	10.435	50.00	27.38	Fail
z4	9.063	60	10.796	60.00	19.122	Fail

Run Tests

● Multi-point Shots
○ Selected Point Only

☐ Show Phasors

Fault Type

☐ AN ☐ BN ☐ CN
☑ AB ☑ BC ☑ CA
☑ ABC

Figure 12. Example for distance zone 1 error for off-nominal frequency conditions (difference between system and tracking frequencies)

- *Evaluation of elements, responding to harmonics with attention to behavior such as harmonic restraint or inhibit for transformer differential relays, THD measurement etc behavior during off-nominal frequency.*
- *Evaluation of elements, directly responding to frequency measurements such as underfrequency, overfrequency, rate of frequency change, Volts per Hertz etc behavior during off-nominal frequency.*
- *Evaluation of differential relay response to off nominal frequency conditions accordingly points of interest indicated above.*

Figure 13 below illustrates example of the relay functions evaluation for off-nominal conditions. Results of such testing are useful for evaluating necessary setting margins for a given relay.

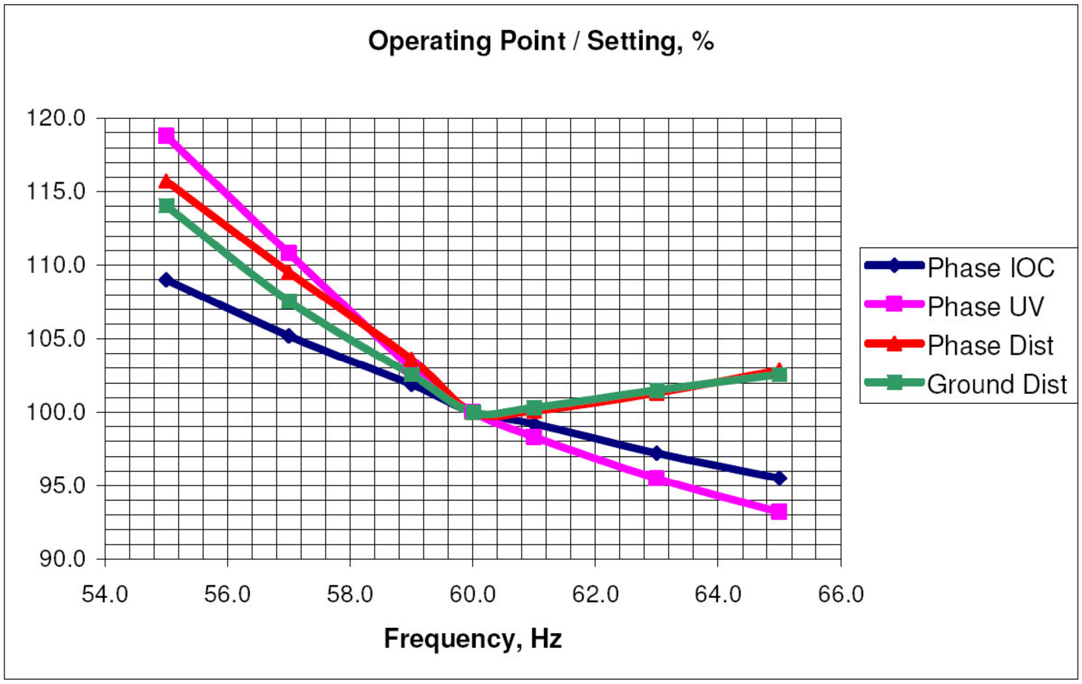


Figure 13. Example of overall relay elements accuracy for transient off-nominal frequency conditions (difference between system and tracking frequencies)

9. Summary

Before 2003 blackout, protection engineers didn't pay much attention to this phenomenon; it was not even part of relay acceptance testing. However, multiple nuisance trips during this blackout, forced system operators to look at this problem and re-evaluate relay performance for such conditions. In fact, Federal Energy Regulatory Commission (FERC) has appealed to the IEEE Power System Relaying Committee to evaluate system relay protection response to off-nominal frequency conditions and come up with a report and recommendations to avoid misoperations during major system disturbances.

As it was demonstrated in this paper, practically all protection elements are impacted by off-nominal frequency conditions; some to a grater extent than others. This paper has explained how the microprocessor relay adjusts sampling frequency to the system frequency to minimize errors. It also has given some insights to the protection engineer on how to test in order to evaluate a particular relay response during such conditions. The potential Impact on major protection functions was revealed. It is clear that different relay designs may be more or less vulnerable to off-nominal frequency conditions.

10. References

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2. *GE Publication GEK-113349, 2007, L90 Line Differential Relay, Instruction Manual.*

3. *Bogdan Kasztenny, "Distance Protection of Series Compensated Lines – Problems and Solutions", Western Protective Relay Conference, Spokane, WA, 2001*
4. *Roberto Cimadavilla et al, "Adapting Protection to Frequency Changes", Western Protective Relay Conference, Spokane, WA, 2005.*

BIOGRAPHIES

Bogdan Kasztenny *holds the position of Protection and System Engineering Manager for the protective relaying business of General Electric. Prior to joining GE in 1999, Dr. Kasztenny conducted research and taught protection and control at Wroclaw University of Technology, Texas A&M University, and Southern Illinois University. Between 2000 and 2004 Bogdan was heavily involved in the development of the Universal Relay™ series of protective IEDs. He authored more than 160 papers, is the inventor of several patents, Senior Member of the IEEE, and the Main Committee of the PSRC. Dr. Kasztenny is a registered professional engineer in the province of Ontario. In 1997, he was awarded a prestigious Senior Fulbright Fellowship. In 2004 Bogdan received GE's Thomas Edison Award for innovation*

Dale Finney *began his career with Ontario Hydro where he worked as a protection and control engineer. Since 1999, he has been employed as an applications engineer with GE in Markham Ontario. His areas of interest include generator protection, line protection, and substation automation. Dale has a Bachelor of Engineering degree from Lakehead University and a Master of Engineering degree from the University of Toronto. He is a registered professional engineer in the province of Ontario, a member of the PSRC, and a senior member of the IEEE.*

Ilia Voloh *received his Electrical Engineer degree from Ivanovo State Power University, Soviet Union. He then was for many years with Moldova Power Company in various progressive roles in Protection and Control field. Currently he is an Application Engineer with GE Multilin. His areas of interest are current differential relaying, phase comparison, distance relaying and advanced communications for protective relaying. Ilia authored and co-authored more than 10 papers presented at major North America Protective Relaying conferences. He is a member of the PSRC, and a senior member of the IEEE.*

BACK TO THE TABLE OF CONTENTS