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Performance Specification and Testing of Transmission Line Relays for Frequency Response

Power System Relaying Committee

Special Report
WG D-22 of the
Line Protection Subcommittee

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1. Introduction

This report proposes a test that can be applied to any type of transmission line distance relay to ascertain its response to off-nominal frequency and abnormal system voltages. The line distance relay measures electrical circuit impedance between the relay location and the point of fault as defined in IEEE C37.113. The working group has included frequency ranges above as well as below nominal to be included within the test. It is the opinion of the working group that data obtained from the tests can provide transmission protection engineers with information to make an assessment of relay security and dependability during frequency and voltage excursions. The working group is not suggesting that this new test should be applied as a “pass/fail” test to transmission protection relays but only that it is a step forward in the process of developing tools/tests to aid the utility engineer in evaluating relay performance. Any such test should be thoroughly evaluated and experience gained before giving credence to its results.

1.1. System Conditions that Spawned a NERC Request

As the August 14, 2003 cascade and blackout unfolded, several lines tripped via impedance relays in a way that could not be characterized as a fault, an overload, a voltage collapse, or instability. The relays were based on a variety of operating principles and designs – digital, discrete component electronics and electromechanical.

The NERC Blackout Recommendation Review Task Force (BRRTF) noted that during the 2003 Blackout, four electromechanical relays and five digital relays operated in Ohio due to declining frequency. The first observed instance was a 345 kV line in northwestern Ohio which tripped while experiencing low voltage and rapidly declining frequency. Rapid frequency decline in the area is the suspected reason for this transmission line relay operation. Several impedance relays tripped other transmission lines while in this same system condition as the cascade continued. Two 138 kV lines tripped via electro-mechanical distance relays as relay current and voltage magnitudes decreased. These relays were electro-mechanical distance relays with a mho type operating characteristic. Preliminary conclusions suggested a propensity of some distance relays to operate at low system frequencies.

Figure 1 graphs the decline in frequency prior to the 345 kV and 138 kV line trips mentioned above. (Unfortunately, no graph of frequency at the time of these line trips is available.) As the cascade propagated, three 345 kV transmission lines tripped separating northern Ohio from Michigan. Figure 1 graphs the decline in system frequency as these three 345 kV tie-lines tripped. Following the separation, the observed rate of frequency decline increased to approximately 2 Hz/s. This is the condition preceding the 345 kV and 138 kV line trips that is suspected to have affected relay performance.

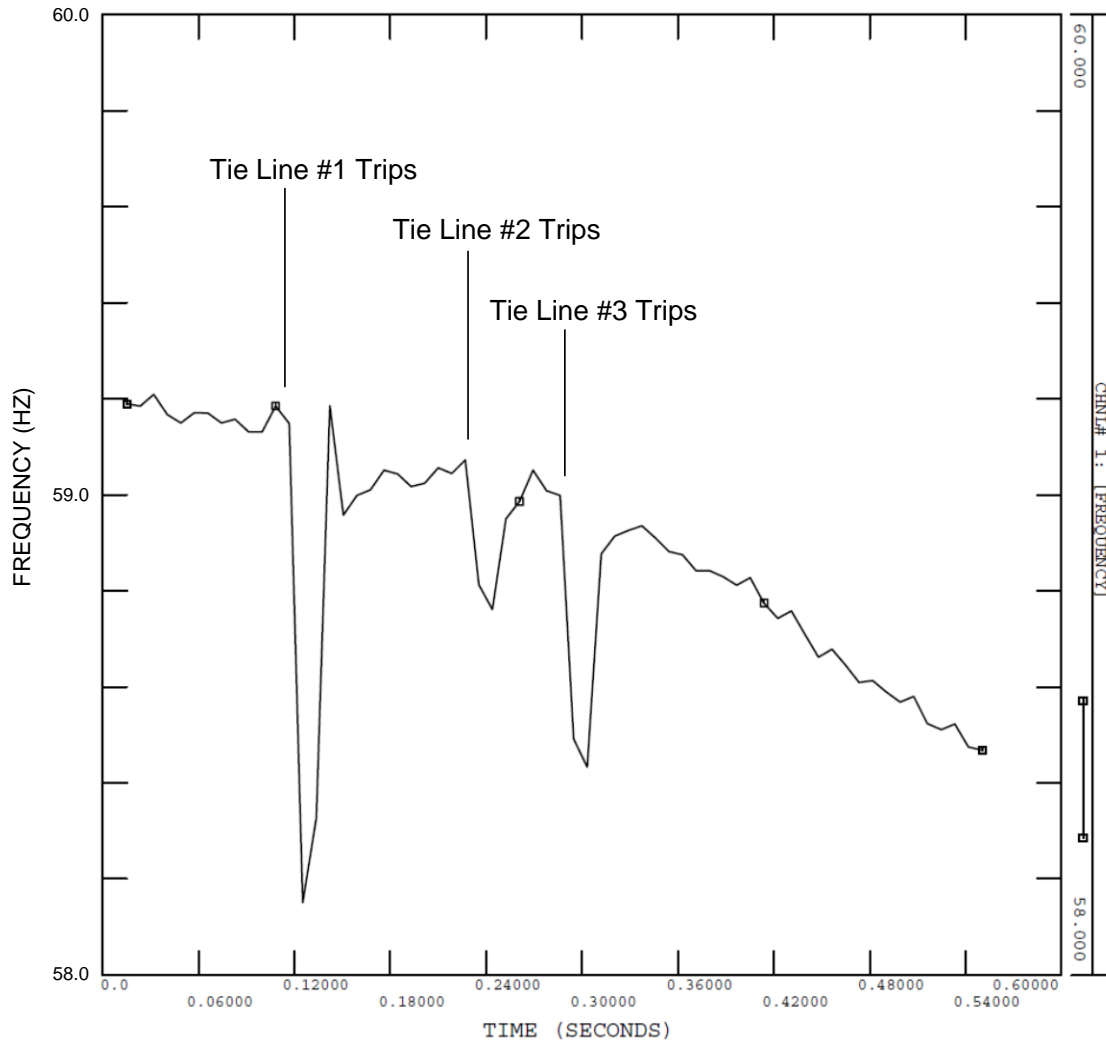


Figure 1: Model of August 14, 2003 Frequency Decline at the Michigan – Ohio Interface

A review of transmission line relay instruction manuals showed that off-nominal frequency specifications are often not published. From a system performance perspective during extreme conditions, such as an imbalance between load and generation, it was in the opinion of the blackout investigators that transmission line relays should be secure against the effects of off-nominal frequency throughout the entire frequency range of the UFLS programs and generator underfrequency tripping schemes.

One of the NERC Blackout Recommendation Review Task Force technical recommendations, TR-18 addresses the issue of relay performance at off-nominal frequency.

“TR – 18: Revise Industry Standards to Establish Under/Over Frequency Design Limits of Operation for Distance Relays

Observation: Comparator logic, generally found in impedance relays, is prone to tripping as frequencies deviate from 60 Hz.

Discussion

Just after East Lima – Fostoria Central 345 kV line tripped, low voltage and rapidly declining frequency occurred in the Toledo area. Transmission lines in the area were carrying very little current with Fostoria Central, the major source now lost. Rapid frequency decline in the area (before Cleveland separated from Toledo) is the suspected reason for these transmission line relay operations. Several impedance relays tripped transmission lines while in this system condition. These relays, including digital and electromechanical, were from a number of different manufacturers and with different principles of frequency operation range for the relays.

Although manufacturers inconsistently apply frequency operating range designs for relays, to maintain system integrity, all relays must operate properly throughout the entire frequency range of the UFLS programs and generator underfrequency tripping schemes.

Recommendation TR–18: Standardize a frequency floor and ceiling within which relays should not trip due to deviations in system frequency. Such a frequency range should be coordinated with UFLS and generator underfrequency tripping schemes. Industry standards such as IEEE Standard C37.90 should be revised to include this limit.”[7]

In April 2006, the North American Electric Reliability Corporation (NERC) requested the IEEE Power System Relaying Committee address two specific issues:

1. that manufacturers of protective relays include within operating specifications:
 - a. In-service minimum and maximum frequency range for in-specification operation,
 - b. Rate-of-change-of-frequency ratings (df/dt) for in-specification operation.
2. that the IEEE PSRC establish minimum parameters for any protective relays designed after approval of a subject standard for:
 - a. In-service minimum and maximum frequency range for in-specification operation,
 - b. Rate-of-change-of-frequency ratings (df/dt) for in-specification operation.

A Task Force was formed at the May 2006 PSRC meeting to address the NERC request and to provide PSRC with their recommendations. The task force recommended to the Line Protection Subcommittee that a working group be formed. The recommendation included this working group assignment.

“Investigate the feasibility of defining a range of frequency and rate-of-change of frequency to be used in a performance specification for protective relaying functions. If this proves feasible then the WG will pursue the feasibility of developing a test process for transmission line relays subjected to off frequency disturbance including rate-of-change of frequency conditions during stressed system conditions. At the January 2007 PSRC meeting the Transmission Line Protection Subcommittee accepted the recommendation to form a working group.”

This working group determined it was feasible to define ranges of frequency and rate-of-change of frequency that could be used in a performance specification for protective relaying functions. The working group developed test processes for transmission line relays for off frequency and rate-of-change of frequency including the simulated presence of depressed voltage.

2. Protection Functions to be Tested

This report proposes a test that can be applied to any type of transmission line distance relay to ascertain its response to off-nominal frequency and abnormal system voltages. The line distance relay measures electrical circuit impedance between the relay location and the point of fault as defined in IEEE C37.113. The following distance protection functions can be considered as candidates for the test.

- Mho distance function (both phase and ground)
- Reactance distance function (both phase and ground)
- Quadrilateral distance function (both phase and ground)
- Blinder function
- Directional comparator function

The tests are functional and all types of distance relays can be tested - electro-mechanical, discrete component electronic and digital. The Working Group considered several ways to propose and format the tests. It was our opinion that the test objectives could be best reached by creating voltage and current waveforms that include frequency and voltage ramping via a spreadsheet calculation and then creating COMTRADE© files from these calculations. Section 3 presents the mathematics and concludes in subsection 3.5 by describing the details of the COMTRADE© calculator.

3. Basics of Mho Element Implementation

A conventional distance element with a mho characteristic is implemented by defining one operating quantity and one polarizing quantity as in Equation (1):

$$\begin{aligned} S_{op} &= Z_L \bullet I_r - V_r \\ S_{pol} &= V_{pol} \end{aligned} \quad (1)$$

Z_L is the element reach, I_r is the current at the input of the element, and V_r is the voltage at the input of the element. Conventional voltage polarizing quantities include self-polarization, cross-polarization, polarization by positive sequence voltage (PSV) (V_1) and polarization by PSV memory (V_{1M}).

The element will assert when the scalar product between the operating quantity and the polarizing quantity is positive or:

$$\text{Re} ([Z_L * I_r - V_r] * \text{conj}(V_{pol})) \geq 0 \quad (2)$$

In Equation (2), "Re" represents "real part of " and "conj" represents "conjugate of." The scalar product is tantamount to implementing an angle comparator. If the angle between the polarizing quantity and the operating quantity is less than 90° , the element will assert. Using the A-B loop as an example, the voltage phasor V_r and the current phasor I_r depend upon which impedance loop among the 6 possible loops (3 for phase faults and 3 for ground faults) is calculated. For a phase element covering the phases AB fault loop, V_r is equal to $(V_A - V_B)$ and I_r is equal to $(I_A - I_B)$. Using this information and substituting it into equation (1), we obtain equation (3):

$$\begin{aligned} S_{op} &= Z_L \bullet (I_A - I_B) - (V_A - V_B) \\ S_{pol} &= V_{pol} \end{aligned} \quad (3)$$

The polarizing quantity could take one of the four possible implementations as shown by equation (4):

$$V_{pol} = \begin{cases} \text{Self - polarization} & \Rightarrow V_A - V_B \\ \text{Cross - polarization} & \Rightarrow V_C \angle -90^\circ \\ \text{Polarization by PSV} & \Rightarrow V_1 \\ \text{Polarization by PSV memory} & \Rightarrow V_{1M} \end{cases} \quad (4)$$

The calculation of the PSV memory phasor depends upon the relay design and will vary from one relay manufacturer to another. For the A-B loop in one design, the polarization PSV memory phasor is a combination of the present PSV phasor and a memory phasor per Equation (5)

$$V_{1M}(t_0) = (1 - \alpha) \bullet V_1(t_0) \angle 30^\circ + \alpha \bullet V_{1M}(t_0 - \Delta T) \quad (5)$$

In equation 5, α is the percentage memory. The present sample is represented by t_0 and the previous sample is represented by $(t_0 - \Delta T)$. An example of an alternate design is to use a delayed positive sequence voltage phasor as the memory voltage.

$$V_{1M}(t_0) = V_1 \angle 30^\circ(t_0 - \Delta T) \quad (6)$$

The memory is frozen when a change in the system has been detected. This previous solution is analogous to having 100% memory polarization during a freeze condition. The system change that triggers the memory latch depends upon the element design and will vary from one relay to another. [5]

4. Impact of Frequency Swings on Distance Functions with Memory Polarization

The impact of frequency excursions on microprocessor based distance functions with memory polarization and the causes for misoperations has been extensively described in recent conference papers [1,2,3]. This section describes the basic technical issue that leads to the element misoperation, namely memory polarization. Elements based on electro-mechanical or static technologies have the same limitations, but the physical phenomena must be described in different terms.

The typical methods for developing a memory voltage are to use filters, past data, or to "freeze" the memory voltage based upon some detection criteria. When using filters or past data, the memory voltage is made up of present and past data, therefore, when the frequency is changing, the memory voltage will actually be made of samples from the currently measured frequency and samples from the measured frequency some time ago. If these frequencies do not match, then the memory voltage will lose "synchronism" with the presently sampled voltages. As the rate of change of frequency increases, the phase angle difference increases at a faster rate.

When using a "freeze" technique, if the initiating condition has not triggered, there is really no problem if it operates like a self-polarized relay. However, if the triggering action has occurred, then the memory voltage is "locked" and any change in frequency, even with an updated sample rate, will result in a phase shift.

See the **Appendix** for further discussion of the purpose and principle of memory polarization.

4.1 The Impact of Sampling Frequency on Voltage & Current Phasor Calculation

The phasors supplied to the microprocessor based distance elements are acquired using digital filters. A digital filter is supplied with sampled values of the waveform. The output from the digital filter is used to compute the voltage and current phasors. The data input waveform uses a sampling frequency typically corresponding to an integer multiple of system frequency. For example, a sampling frequency of 960 Hz corresponds to a sampling frequency of 16 times the system nominal frequency for a 60 Hz system. Microprocessor based relays have logic that tracks this system nominal frequency to ensure that the sampling frequency is always a fixed integer value of the system frequency (16 for this example). To accomplish this, the frequency tracking logic (or algorithm) measures the network frequency and adjusts the sampling frequency accordingly. There is a delay that varies with the relay design in the sampling frequency adjustment. In steady state, the sampling frequency is a fixed multiple of the actual system frequency. When a frequency swing occurs, there will be a frequency difference between the network frequency and the sampling frequency depending on the rate-of-change of frequency. This discrepancy will introduce some errors in the phasor calculation depending upon the mismatch between the sampling frequency and the network frequency.

4.2 The Impact of the Sampling Frequency on the Polarizing Voltage

When two waveforms with a frequency difference Δf are sampled with the same sampling frequency (being a multiple to one of them for example) the angle between the two corresponding phasors will rotate at a speed proportional to the frequency difference Δf . The same phenomenon is observed if the same waveform is sampled at two different sampling frequencies. When there is a memory in the polarizing voltage, this is precisely the phenomenon that is taking place. When there is a frequency swing, the phasors corresponding to the operating quantity and the phasors corresponding to the polarizing quantity are not sampled at the same frequency because there is a proportion of the polarizing waveform that has been acquired earlier when the waveform had a different frequency. The angle between the two phasors (operating and polarizing) will start to shift from the steady state value not because of a change in the power system conditions but because of the mismatch in the sampling frequencies of the waveforms associated with the two phasors. Ultimately, due to the rotation between the two vectors, the angle between the operating and polarizing phasors could become smaller than 90° and the mho element will misoperate. References [3], [4], and [5] investigate and describe thoroughly this phenomenon.

If there is no memory effect in the polarizing quantity, all waveforms in the operating and polarizing quantities are digitized using the same sampling frequency and there is no shift of the angle between the two operating and polarizing phasors. Therefore, mho elements with self and cross-polarization are not affected by frequency errors. Mho elements that include a percentage of memory in the polarizing quantity are affected by network frequency swings and could misoperate under certain conditions.

4.3 Impact of the Memory Percentage in the Polarizing Quantity

When computing the polarizing voltage using positive sequence voltage with memory as indicated by equations (5) and (6), there is, embedded in the design of the mho element, a percentage of memory represented by α . In equation (5), the percentage α could vary between 0 and 100%. In equation (6), α has a value of 100% because the memory is latched following some event. It is obvious that the higher the value of the percentage α , the higher the likelihood of the negative impact of a frequency swing on the mho element.

4.4 Impact of the Line Loading

The location of the element apparent impedance or line loading at the inception of the frequency swing is another factor that will have an impact on the mho element response to a frequency swing. The higher the line loading or the closer the apparent impedance to the relay reach, the higher the probability of a misoperation. Consider Figures 2 and 3 where the steady state characteristics of mho-phase elements are represented in the complex plane. The polarizing quantity is assumed to be a positive sequence voltage with memory. Figure 3 represents a steady-state characteristic where the line loading is greater than in Figure 2. In Figure 3, the angle θ_2 between the operating and polarizing vectors is much closer to 90° than the corresponding angle, θ_1 , in Figure 2. Consequently, it will take a very small amount of frequency shift to cause a rotation between the two phasors so that the angle between them will become less than 90° causing the mho element to misoperate. The situation would be about the same even if a load encroachment characteristic had been implemented. In this latter situation, the issue would be how far the load or apparent impedance is from the load encroachment characteristic boundary.

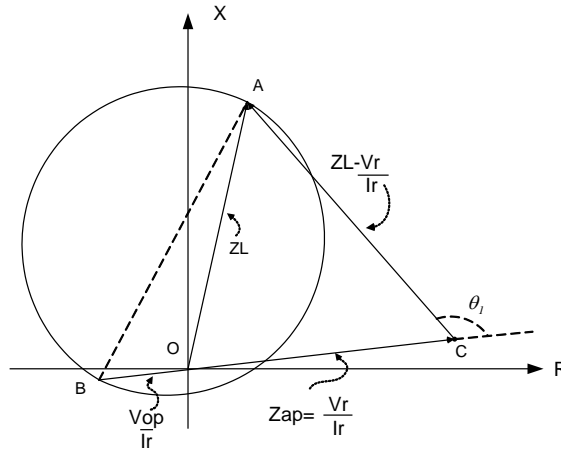


Figure 2. Steady-state mho element characteristic with moderate or light load

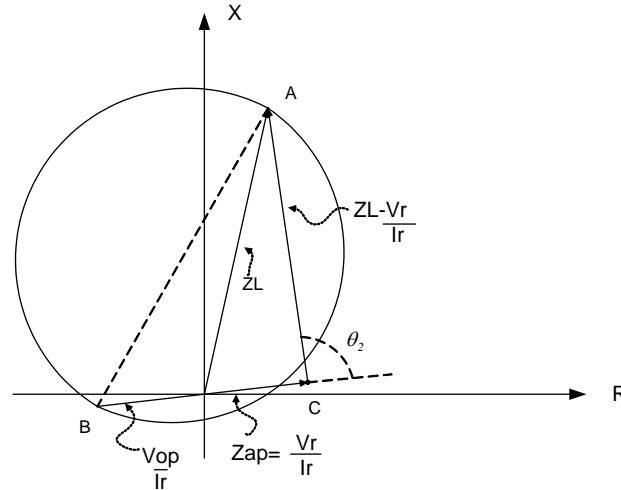


Figure 3. Steady-state Mho element Characteristic with Heavy Load

4.5 Impact of the rate-of-change of the network frequency

It is obvious that the higher the rate-of-change of the frequency and the longer the duration of the frequency error, the higher the likelihood of an impact of a frequency swing on a mho element.

4.6 Worst-case Scenario

From the preceding sections one can conclude that a combination of the following conditions would constitute a worst-case scenario:

- The mho element with the furthest reach
- A heavily loaded line
- A high proportion of memory in the polarizing quantity
- A ramping network frequency with a high rate-of-change (Hz/s)

From the preceding considerations it may seem microprocessor-based distance relays are exposed to a variety of problems during off-nominal frequencies. The reality is that these relays support frequency tracking / compensation and by virtue of it are actually less prone to the problem compared with analog relays. Under stressed system conditions different implementations of the frequency tracking/compensating schemes may respond differently. In particular under a large rate-of-change of frequency some implementations may either stop tracking at certain upper or lower limits, or considerably lag the actual and fast changing system frequency. 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 measures the frequency accurately, it regains its absolute precision even though the system frequency is not at the nominal. As a result, the off-nominal frequency issues occur primarily during fast frequency excursions when the relay may apply security averaging and adjust its tracking frequency intentionally slower compared with the changes in the power system. For example some of the islands during the 2003 blackout showed frequency changes in excess of 30 Hz/sec for duration of 100-200 ms when coasting down before a total disconnection of generators and loads.

Some relays would not allow such excessive 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 would change well within the design limits of the relay frequency tracking / compensation mechanism. This design allows the tracking to catch up to the system frequency and maintain correct measurements or show a finite frequency error resulting from the lag in tracking that is much less than the difference between the actual and nominal frequencies. Unacceptable performance would only occur then if the difference between nominal and actual frequency is extremely large, if frequency tracking is disabled, or if there is no tracking signal input.

4.7 Testing the Distance Function

The most straightforward way to test the response of distance functions to changing system frequency is by injecting phase voltage and current waveforms as their frequency changes according to a prescribed rate-of-change of frequency; a frequency ramp. Three issues have to be taken into consideration here:

1. The slope of the frequency ramp with units of Hz/s. The higher the slope, the more stringent the test.
2. The duration of the frequency ramp.
3. The setting of the distance function.

The user normally has neither control of the memory percentage that is normally embedded in the element design nor control of the type of polarization used by the relay manufacturer.

4.8 Creating COMTRADE© Files

Three-phase voltage and current waveforms with various loading and various ramping frequencies can be mathematically synthesized and the resulting arrays of sampled values can be used to create COMTRADE© files. Distance functions can be tested with inputs defined by these COMTRADE© files using standard testing equipment with waveform playback capabilities.

Consider a voltage, $v(t)$, that is a sine wave function of time, t , of the form:

$$v(t) = V \sin[2\pi f_{nom} + \theta(t)] \quad (7)$$

$$\theta(t) = 2\pi \frac{slope}{2} t^2 \quad (8)$$

This sine wave has then a ramping frequency of the form:

$$frequency(t) = f_{nom} + slope \bullet t \quad (9)$$

where f_{nom} is the nominal frequency of the system and “slope” is the linear frequency variation in Hz/s and can be either positive or negative. As shown in Figure 4, the function $\theta(t)$ is given an initial value of f_{nom} over an interval of time T_0 to allow the memory to settle to its final value. After this time interval, the desired ramp value is used, but the ramp rate changes gradually over a period of about three cycles. Maximum and minimum values of frequency, if specified for the relay, should be used as operational limits.

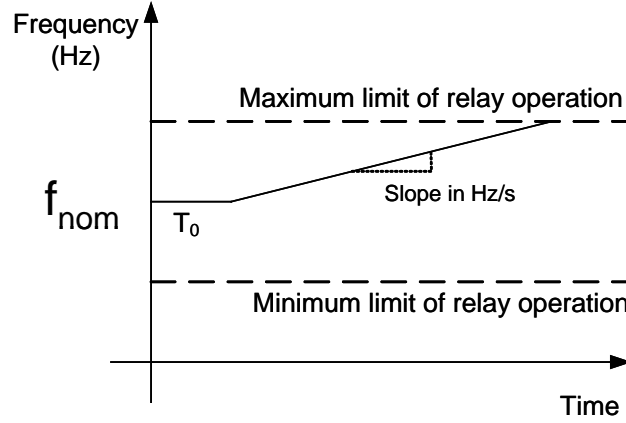


Figure 4: Example of a Ramping Function

The following voltages and currents can be created mathematically:

$$\begin{aligned}
 va(t) &= V \sin(2\pi f_{nom} + \theta(t)) \\
 vb(t) &= V \sin(2\pi f_{nom} + \theta(t) - 120^\circ) \\
 vc(t) &= V \sin(2\pi f_{nom} + \theta(t) + 120^\circ) \\
 ic(t) &= I \sin(2\pi f_{nom} + \theta(t) - \phi) \\
 ib(t) &= I \sin(2\pi f_{nom} + \theta(t) - 120^\circ - \phi) \\
 ia(t) &= I \sin(2\pi f_{nom} + \theta(t) + 120^\circ - \phi)
 \end{aligned}$$

(10)

V and I are secondary values and the secondary load impedance is given as:

$$Z_{LOAD} = \frac{V}{I} \angle \phi \quad (11)$$

Three-phase waveforms corresponding to equation (10) could be created with various values of loading by varying I and various positive and negative values of slope.

For example, the described test could allow the determination of the maximum rate-of-change of frequency the element can sustain before a misoperation for a given reach and system loading. Such a test would not be conclusive for elements that operate on the latching memory principle. An additional condition would have to be created in the signals that would trigger the memory latch before the frequency starts ramping.

5. References - Distance Relay Responses to Off-Nominal Frequency

The following three references focus on the response of distance relays with regard to frequency tracking, compensation, measurement and polarization.

“Frequency Tracking / Compensation and Influence of Frequency Variations,” IEEE PSRC WG C12, Performance of Relaying during Wide-Area Stressed Conditions.[1]

“Polarizing Scheme Adapts to Changing System Conditions, Innovative Solutions Improve Transmission Line Protection,” Daqing Hou, Armando Guzmán, Jeff Roberts Schweitzer Engineering Laboratories, Inc., Pullman, WA USA.[2]

“Adapting Protection to Frequency Changes, Roberto Cimadevilla, ZIV, Vizcaya - Spain; Rafael Quintanilla, ZIV, Vizcaya – Spain; S. Ward, RFL Electronics Inc., Boonton, NJ, presented at Western Protective Relay Conference, Spokane, WA, October 25 - 27, 2005.[3]

6. Performance Indices for the Tested Functions

The Comtrade© Test provides for the testing of the distance relay at various angles along the relay’s characteristic. The tests are for security and trip dependability. Based on the test results to-date, the Working Group recommends that the tested relay be held to a +/- 10% variance from its characteristic reach at a specific load angle when subjected to off-nominal frequency and voltage variations.

7. Description of Security and Dependability COMTRADE© Tests

Four tests using COMTRADE© format were developed. The plot activity is an action whereby current at a specific angle with respect to voltage is increased until the relay operates. The activity is performed every 10° with respect to current lagging voltage.

7.1 Test 1 – Security (Response to Change in Frequency at a Given Voltage)

1. Set distance function under test at a specific value (e.g., 5 ohms secondary at 75° maximum reach angle)
2. Hold Voltage constant at 1.0, 0.95, 0.9 and 0.85 per unit
3. Determine a current at a specific angle (e.g., 30°) 10% outside the relay's operating boundary (i.e., at an impedance value 10% greater than the relay characteristic at that specific angle). This current is determined at the voltages above (1.0, 0.95, 0.9 and 0.85 pu)
4. Ramp frequency at rates of 1, 2, 4 and 8 Hz/s from 60 Hz to 56 Hz. and then return to 60 Hz at 1 Hz/s.
5. Ramp frequency at rates of 1, 2, 4 and 8 Hz/s from 60 Hz to 64 Hz. and then return to 60 Hz at 1 Hz/s.
6. Relay should not operate

Figure 15a demonstrates Test 1 where voltage is held constant at 0.90 pu while frequency is varied from 60 Hz to 56 Hz at a rate of -4 Hz/s and then ramped back to 60 Hz at 1 Hz/s.

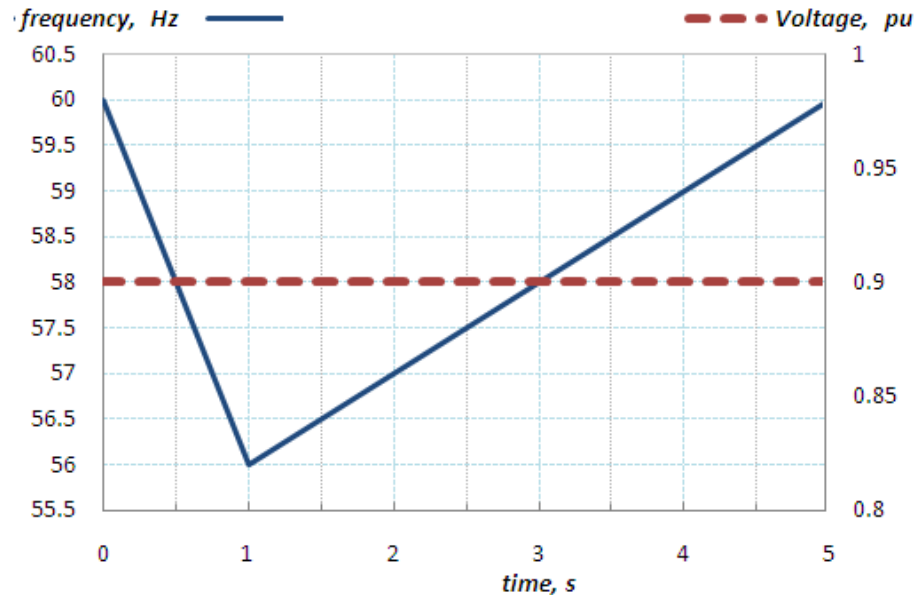


Figure 15a: Test 1 – Voltage is Held Constant at a Specified Voltage while Frequency is Ramped at a Specified Rate

7.2 Test 2 – Security (Response to Change in Voltage & Change in Frequency)

1. Set distance function under test at a specific value (e.g., 5 ohms secondary and 75° maximum reach angle)
2. Determine a current at a specific load angle (e.g., $\pm 30^\circ$) 10% outside the relay's operating boundary (i.e., at an impedance value 10% greater than the relay characteristic at that specific angle). This current is determined at 0.85 pu voltage
3. Decrease voltage at a linear rate from 1.0 per unit to 0.85 per unit during a time as determined by the rate-of-change of frequency (e.g., at 2 Hz/s, frequency will decrease from 60 Hz to 56 Hz in 2 seconds. Over these 2 seconds decrease voltage from 1.0 pu to 0.85 pu.)
4. While varying the voltage over these time frames, vary frequency at rates of 1, 2, 4 and 8 Hz/s as frequency varies from 60 Hz to 56 Hz. and then return to 60 Hz at 1 Hz/s.
5. While varying the voltage over these time frames, vary frequency at rates of 1, 2, 4 and 8 Hz/s as frequency varies from 60 Hz to 64 Hz. and then return to 60 Hz at 1 Hz/s and voltage to 1.0 pu at the same rate.
6. Relay should not trip.

Figure 15b demonstrates how voltage can be ramped while frequency is ramping. Figure 16 demonstrates how a relay failed the security test of either test 1 or test 2. In this example, the relay tripped errantly when the frequency dropped to 56.5 Hz corresponding to point 4. Note that for Figures 15a and 15b in the actual COMTRADE© Calculator, there is a pre-event constant voltage and nominal frequency impressed upon the device under test.

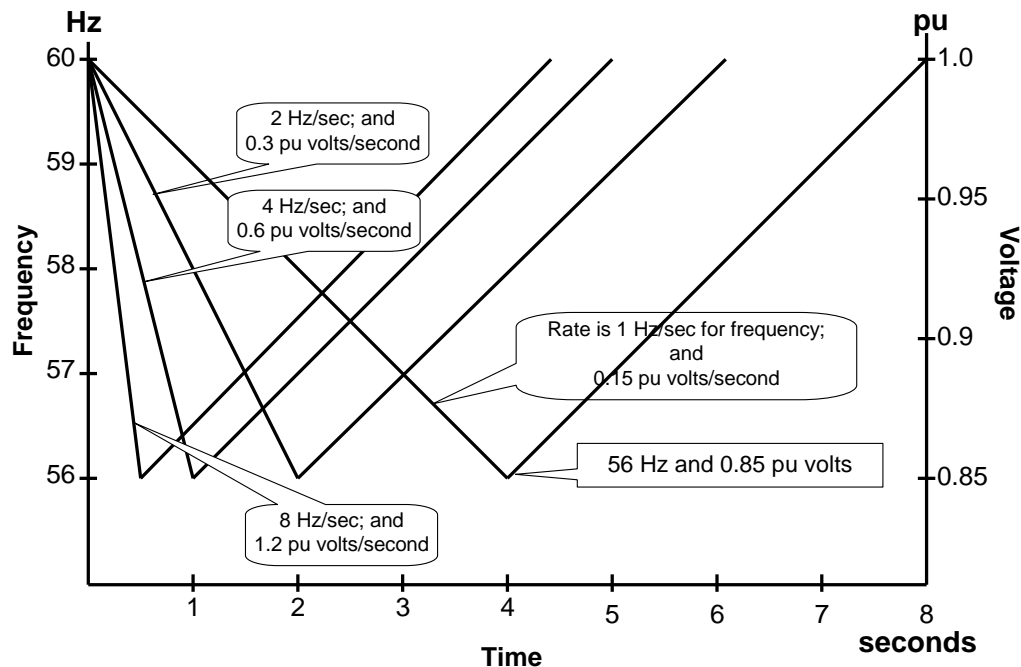


Figure 15b: Tests 1,2,3 Ramp Frequency at a Specific Rate that then Determines the Voltage Ramp Rate

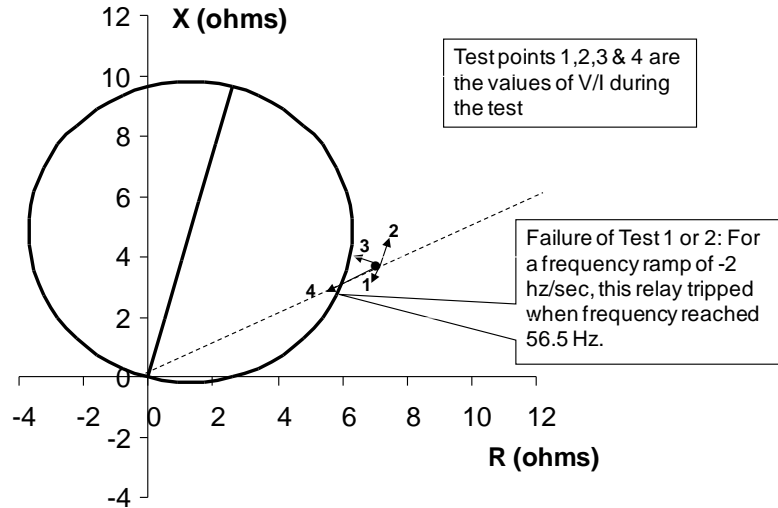


Figure 16: Example of a Relay that Fails the Test 1 or 2 - Security Tests

7.3 Tests 3 & 4 – Dependability (Response to change in voltage & change in frequency during a simulated fault)

1. Set distance function under test at a specific value (e.g., 5 ohms secondary)
2. Repeat Test 1 and Test 2 having determined a test current at a specific load angle (e.g., $+30^\circ$) such that the impedance point is 10% inside the relay's characteristic reach at the test angle..
3. Verify relay's trip performance as frequency varies from 60 Hz to 56 Hz and then 60 Hz to 64 Hz at 1, 2, 4 and 8 Hz/s.
4. Relay distance function output should remain continuous through the changes in frequency and voltage.

Figure 17 demonstrates a relay that has failed the trip dependability test. The relay errantly “dropped out” when frequency dropped to 56.5 Hz.

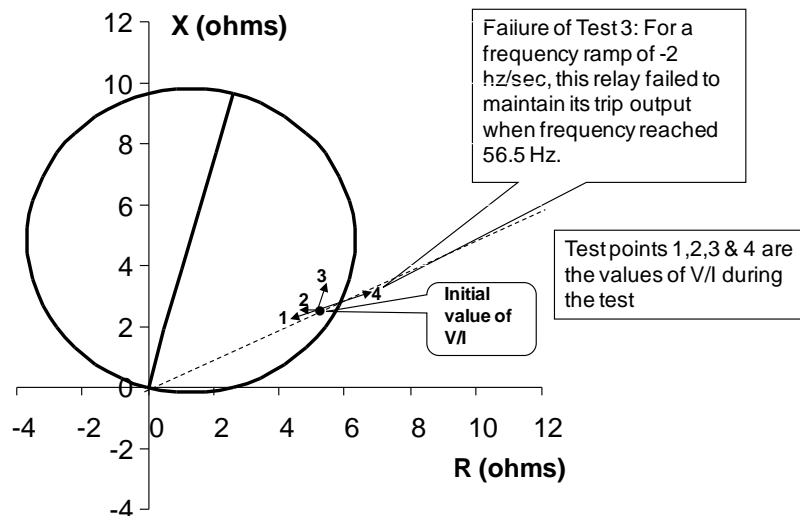


Figure 17: Example of a Relay that Fails the Tests 3&4 Dependability Tests

8. COMTRADE® Calculator

To implement the test cases described above a utility application in MS Excel is available for the creation of COMTRADE® files for Test 1, 2 and 3 described above for use in testing the relays as shown in Figure 18. The nominal voltage, frequency and current are entered, as well as the relay reach and angle settings and the load margin of $\pm 10\%$ at some load angle like 30° for the initial point. The initial impedance point is calculated, as well as the current corresponding to the point. The test case is selected from a dropdown box, which automatically sets the frequency and voltage test parameters.

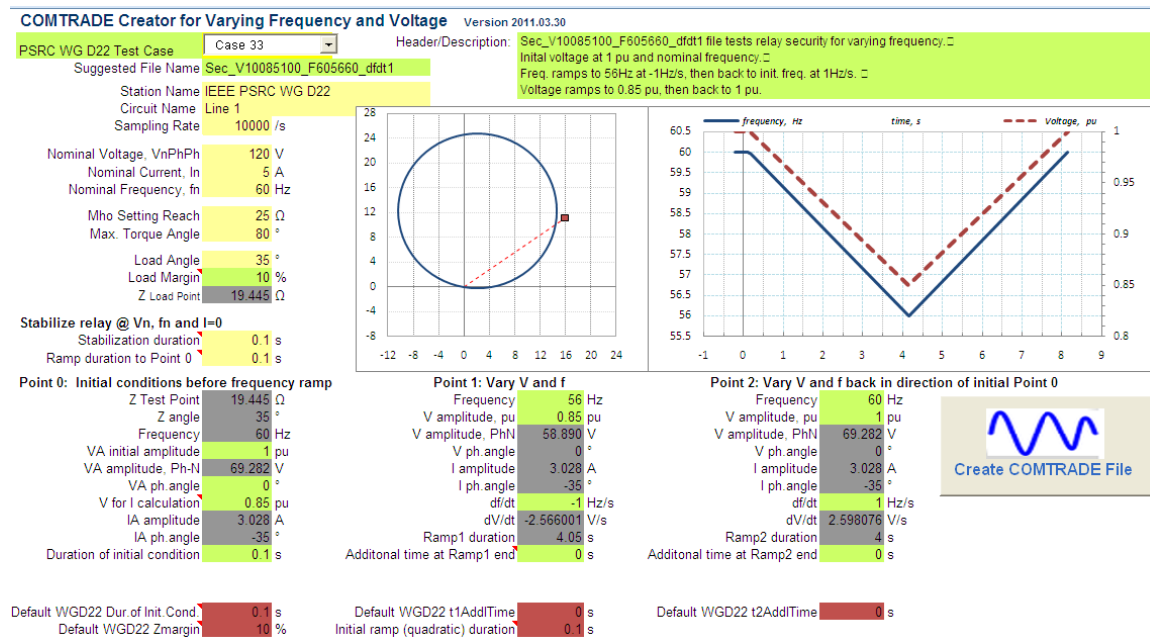


Figure 18: COMTRADE® Calculator

There are 40 test cases for dependability and 40 test cases for security as shown in the table below. The test case name gives an indication of the voltage and frequency ramps. For example test case 35 with the name “Sec_V10085100_F605660_dfdt4” indicates that it is a test for security where the frequency starts at 60Hz, ramps down to 56 Hz at a slope, df/dt , rate of 4 Hz/s and returns to 60 Hz while the voltage starts at 100% of nominal, ramps down to 85% and returns to 100%.

For security the impedance point is 10% outside the mho circle while for dependability the impedance point is -10% which is inside the mho circle.

Test Cases for Security			Test Cases for Dependability		
Case Number & Name		Load Margin (%)	Case Number & Name		Load Margin (%)
Case 1	Sec_V100100100_F605660_dfdt1	10	Case 41	Dep_V100100100_F605660_dfdt1	-10
Case 2	Sec_V100100100_F605660_dfdt2	10	Case 42	Dep_V100100100_F605660_dfdt2	-10
Case 3	Sec_V100100100_F605660_dfdt4	10	Case 43	Dep_V100100100_F605660_dfdt4	-10
Case 4	Sec_V100100100_F605660_dfdt8	10	Case 44	Dep_V100100100_F605660_dfdt8	-10
Case 5	Sec_V959595_F605660_dfdt1	10	Case 45	Dep_V959595_F605660_dfdt1	-10
Case 6	Sec_V959595_F605660_dfdt2	10	Case 46	Dep_V959595_F605660_dfdt2	-10
Case 7	Sec_V959595_F605660_dfdt4	10	Case 47	Dep_V959595_F605660_dfdt4	-10
Case 8	Sec_V959595_F605660_dfdt8	10	Case 48	Dep_V959595_F605660_dfdt8	-10
Case 9	Sec_V909090_F605660_dfdt1	10	Case 49	Dep_V909090_F605660_dfdt1	-10
Case 10	Sec_V909090_F605660_dfdt2	10	Case 50	Dep_V909090_F605660_dfdt2	-10
Case 11	Sec_V909090_F605660_dfdt4	10	Case 51	Dep_V909090_F605660_dfdt4	-10
Case 12	Sec_V909090_F605660_dfdt8	10	Case 52	Dep_V909090_F605660_dfdt8	-10
Case 13	Sec_V858585_F605660_dfdt1	10	Case 53	Dep_V858585_F605660_dfdt1	-10
Case 14	Sec_V858585_F605660_dfdt2	10	Case 54	Dep_V858585_F605660_dfdt2	-10
Case 15	Sec_V858585_F605660_dfdt4	10	Case 55	Dep_V858585_F605660_dfdt4	-10
Case 16	Sec_V858585_F605660_dfdt8	10	Case 56	Dep_V858585_F605660_dfdt8	-10
Case 17	Sec_V100100100_F606460_dfdt1	10	Case 57	Dep_V100100100_F606460_dfdt1	-10
Case 18	Sec_V100100100_F606460_dfdt2	10	Case 58	Dep_V100100100_F606460_dfdt2	-10
Case 19	Sec_V100100100_F606460_dfdt4	10	Case 59	Dep_V100100100_F606460_dfdt4	-10
Case 20	Sec_V100100100_F606460_dfdt8	10	Case 60	Dep_V100100100_F606460_dfdt8	-10
Case 21	Sec_V959595_F606460_dfdt1	10	Case 61	Dep_V959595_F606460_dfdt1	-10
Case 22	Sec_V959595_F606460_dfdt2	10	Case 62	Dep_V959595_F606460_dfdt2	-10
Case 23	Sec_V959595_F606460_dfdt4	10	Case 63	Dep_V959595_F606460_dfdt4	-10
Case 24	Sec_V959595_F606460_dfdt8	10	Case 64	Dep_V959595_F606460_dfdt8	-10
Case 25	Sec_V909090_F606460_dfdt1	10	Case 65	Dep_V909090_F606460_dfdt1	-10
Case 26	Sec_V909090_F606460_dfdt2	10	Case 66	Dep_V909090_F606460_dfdt2	-10
Case 27	Sec_V909090_F606460_dfdt4	10	Case 67	Dep_V909090_F606460_dfdt4	-10
Case 28	Sec_V909090_F606460_dfdt8	10	Case 68	Dep_V909090_F606460_dfdt8	-10
Case 29	Sec_V858585_F606460_dfdt1	10	Case 69	Dep_V858585_F606460_dfdt1	-10
Case 30	Sec_V858585_F606460_dfdt2	10	Case 70	Dep_V858585_F606460_dfdt2	-10
Case 31	Sec_V858585_F606460_dfdt4	10	Case 71	Dep_V858585_F606460_dfdt4	-10
Case 32	Sec_V858585_F606460_dfdt8	10	Case 72	Dep_V858585_F606460_dfdt8	-10
Case 33	Sec_V10085100_F605660_dfdt1	10	Case 73	Dep_V10085100_F605660_dfdt1	-10
Case 34	Sec_V10085100_F605660_dfdt2	10	Case 74	Dep_V10085100_F605660_dfdt2	-10
Case 35	Sec_V10085100_F605660_dfdt4	10	Case 75	Dep_V10085100_F605660_dfdt4	-10
Case 36	Sec_V10085100_F605660_dfdt8	10	Case 76	Dep_V10085100_F605660_dfdt8	-10
Case 37	Sec_V10085100_F606460_dfdt1	10	Case 77	Dep_V10085100_F606460_dfdt1	-10
Case 38	Sec_V10085100_F606460_dfdt2	10	Case 78	Dep_V10085100_F606460_dfdt2	-10
Case 39	Sec_V10085100_F606460_dfdt4	10	Case 79	Dep_V10085100_F606460_dfdt4	-10
Case 40	Sec_V10085100_F606460_dfdt8	10	Case 80	Dep_V10085100_F606460_dfdt8	-10

Additional optional pre-test stages were added for the purpose of stabilizing the relay in order to prevent it from undesirably tripping, when suddenly applying load current especially at a low voltage, before the test starts at $t=0$ as shown in Figure 19. Normal voltage and frequency are first applied and then voltage is ramped down to the specified test value and current is ramped from zero up to the calculated load current. Voltage and frequency values are maintained for a short duration before the ramp starts. The ramp rate gradually changes in a quadratic manner from zero to the specified rate over a period of about 0.05s (settable between 0 to 0.20s) for a more realistic testing.

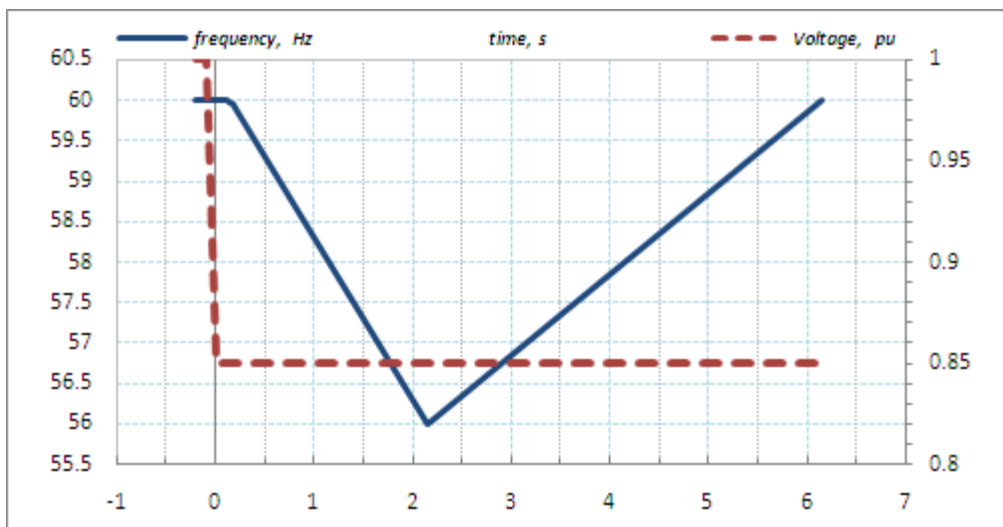


Figure 19: Normal Voltage and Frequency Applied before Ramp

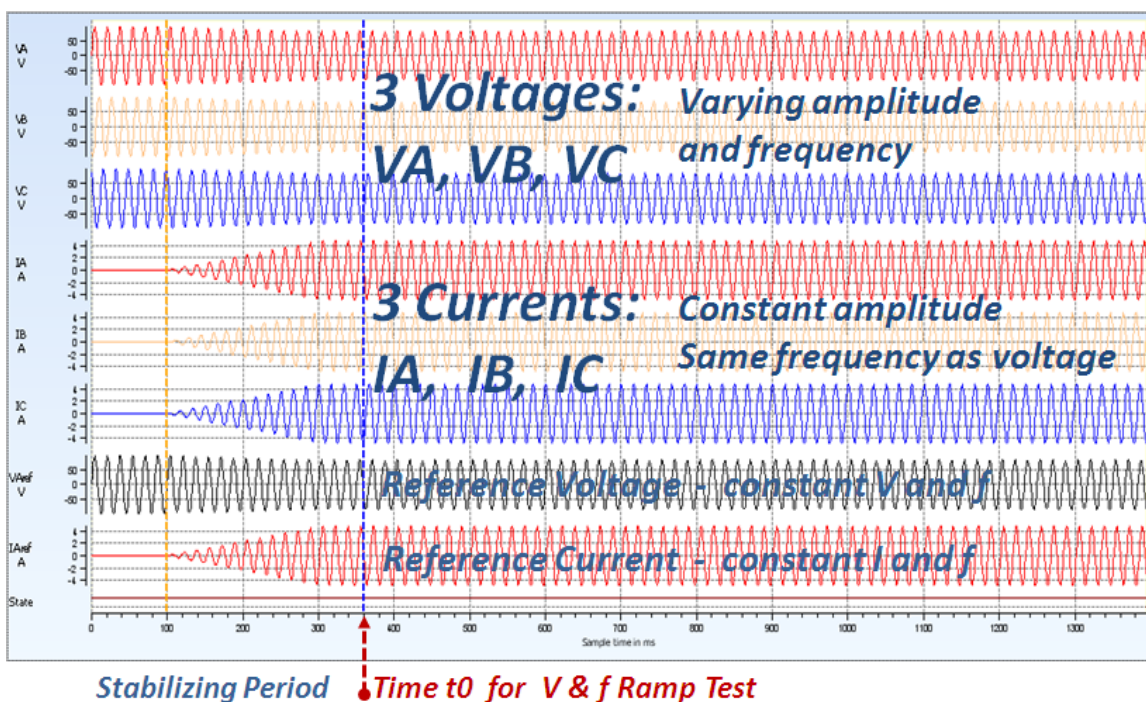


Figure 20. Example of Waveform from a Test Case

9. The Measures of Success/Failure to the Test.

Two factors mainly affect transmission line relay performance during off nominal frequency conditions:

- How memory voltage is updated for distance and directional functions.
- How relays track and adjust to system frequency to minimize phasor errors.

The proposed tests are intended to provide the transmission line relay owner with a measure of relay performance during off nominal frequency conditions. There are security and dependability aspects to the tests. During the security tests, the relay should not operate. During the trip dependability tests should always operate.

10. Report Conclusions

1. Transmission line distance relays should be secure against the effects of off-nominal frequency throughout the entire frequency range of UFLS programs and generator underfrequency tripping schemes. This report proposes a series of tests that can be applied to any type of transmission line distance relay to ascertain its response to off-nominal frequency and abnormal system voltages. It is intended to test the relays within a reasonable range of frequencies and voltages.
2. This report does not consider any specific implementations or solutions, but focuses on establishing benchmark cases for testing performance of distance elements, including memory polarization during related events.
3. The proposed tests are intended to provide the transmission line relay owner with a measure of relay performance during off-nominal frequency conditions. There are security and dependability aspects to the tests. During the security tests, the relay should not operate. During the trip dependability tests the relay should always operate.
4. Distance relays that use the memory polarization function are most impacted by off-nominal frequency conditions. Distance relays that do not use the memory polarization function suffer from minor errors due to frequency excursions.
5. The location of the element apparent impedance or line loading at the inception of the frequency excursion will have an impact on the distance function element response to a frequency excursion.
6. Microprocessor-based distance relays that support frequency tracking and compensation are less prone to inadvertent off-nominal frequency operations than analog relays.

11. References

1. "Frequency Tracking / Compensation and Influence of Frequency Variations," IEEE PSRC WG C12, Performance of Relaying during Wide-Area Stressed Conditions.
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3. "Adapting Protection to Frequency Changes," Roberto Cimadevilla, ZIV, Vizcaya - Spain; Rafael Quintanilla, ZIV, Vizcaya – Spain; S. Ward, RFL Electronics Inc., Boonton, NJ, presented at Western Protective Relay Conference, Spokane, WA, October 25 - 27, 2005.
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6. " Innovative Solutions Improve Transmission Line Protection", Daqing Hou, Armando Guzmán, Jeff Roberts Schweitzer Engineering Laboratories, Inc., Pullman, WA USA.
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Appendix : Purpose and Principle of Memory Polarization

Voltage-polarized directional and distance protection elements require voltage at the relay location for detection of directionality. For close-in faults with no considerable fault resistance, the relay voltage is too low to serve as an adequate source of polarization for the currents, i.e. for the relay to distinguish between currents in the tripping and blocking directions. A bolted three-phase fault depressing all three voltages and preventing any form of effective cross-phase polarization (the use of healthy phase voltages) is an ultimate case supporting the use of memory polarization.

The premise of memory polarization is to use the pre-fault voltage to estimate or predict the phase of the fault voltage. Note, that this approach is based on estimation or approximation, and not on exact rules derived from the network. Also, the principle does not attempt to and cannot estimate the magnitude of the voltage, just its phase. The principle is based on the following three fundamental assumptions and works very well as long as these assumptions hold true:

1. The phase of the equivalent electromotive source behind the relay does not change considerably due to the fault, and for the duration of memory polarization.
2. The actual system frequency is known, and preferably constant, allowing the relay to extrapolate accurately the future (fault) phase of the voltage based on the past (pre-fault) voltage.
3. The network in the relay vicinity is such that the occurrence of a fault does not shift the phase of the relay voltage considerably compared with the pre-fault values.

Memory polarization is relatively easy to implement in microprocessor-based relays, but the principle is applicable to any relay technology (static and even electromechanical) and exhibits the same fundamental advantages and drawbacks regardless of the details of implementation. Issues with memory polarization are not limited to microprocessor-based or phasor-based implementations.

In general, the memory polarization circuit or algorithm develops a notion of a past value of the relay voltage and uses this past value for some time into a fault to estimate the phase of the voltage during the fault. Projection of the historical values (pre-fault) into the future (fault) can be implemented via delay circuits, digital filters, freezing the voltage values upon detecting a fault, etc. Note that the memory polarization can be performed on phasors or otherwise filtered values or on instantaneous values.

In any case, the historical values of the voltage (pre-fault values) reflect the phase of the voltage during the fault, only if the source behind the relay does not shift considerably, and the relay applies accurate frequency to extrapolate the past values into the future, and the network in such that the fault does not make the phase of the voltage at the relay much different compared with the source behind the relay. If any of the three key assumptions is violated, memory polarization faces issues up to and including total loss of directionality potentially leading to loss of dependability or security.

Issues with Memory Polarization

A swing in the electromotive source behind the relay yields the memory polarization principle inaccurate. The relay uses a historical value of the voltage and extrapolates it into the future assuming certain frequency, i.e. typically assuming a steady state of the

equivalent electromotive force behind the relay. This assumption is justified in the vast majority of cases at least if the memory action is not longer than few hundreds of milliseconds. However, if the system behind the relay swings, the relay currents swing with the system. When compared with the fixed voltage phase extrapolated from the past and neglecting the swing, these currents would appear forward or reverse depending on the slip frequency and the time elapsed from the moment of establishing the memory. One could understand this phenomenon better by realizing the memory voltage alternates at the assumed frequency while the actual voltage and currents alternate at a different frequency. As a result of this difference, the memory voltage and the currents would rotate against each other and be periodically in phase and out of phase regardless of the true direction of the currents.

Differences between the assumed and actual frequencies yield the memory polarization principle inaccurate. During the fault the currents alternate with the actual frequency. Typically, the memory voltage is used to estimate the phase angle of the fault voltage assuming historical (and potentially different) values of frequency. The mismatch between the two frequencies creates the phenomenon of the currents and the polarizing memory voltage rotating against each other. When they coincide per the element operating principle and settings, a false operation may take place. When they are out of phase, the element may fail to operate even when called upon.

The frequency errors causing issues with memory polarization can happen either because the actual system frequency changes quickly while the relay uses historical or lagging value of frequency, or when the relay measured the frequency with considerable errors just prior to applying memory polarization, or the relay does not measure the frequency at all and only applying the nominal frequency in memory polarization while the power system is at off-nominal frequency.

Network response to faults could yield the memory polarization principle inaccurate. In some cases, occurrence of the fault shifts the voltage at the relay considerably compared with the pre-fault value. Thus, the pre-fault value cannot be used reliably for estimating the voltage phase during the fault. Series compensation, very weak systems, or systems with non-standard short circuit sources could cause considerable shifts in the relay voltage challenging applicability of memory polarization.

As explained above memory polarization works well if the founding assumptions are met. If the assumptions are violated the principle faces limitations up to and including a total loss of security or dependability of the polarized directional or distance elements. This holds true regardless of the relay technology (microprocessor-based, static, or electromechanical) or details of implementation (phasors, instantaneous values, memory established by filtering or freezing, etc.).

Improvements in Memory Polarization

Known remedies to the weaknesses of memory polarization include:

- Mixed mode polarization in which actual (cross-phase) voltage is combined in a favorable, sometimes time-varying proportion, with the memorized voltage.
- Limiting the effective duration of memory polarization to a minimum, typically to the worst-case fault clearing time assuming breaker failure (directional integrity past this time is of secondary importance).
- Not engaging memory at all if the actual voltage is high enough to facilitate proper polarization.
- Fast frequency measurement and usage of actual frequency to produce the polarizing voltage, or an automatic reversal to self-polarization should the relay detect issues with frequency.

This report does not consider any specific implementations or solutions, but focuses on establishing benchmark cases for testing performance of distance elements, including memory polarization, during frequency related events.