Adapting Protection to Frequency Changes

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Abstract

Electric power systems are susceptible to frequency variations. While the US grid generally exhibits a very stable frequency during all but emergency conditions (such as cascading black-outs) there are regions in some countries in which such variations are extremely notable and recurrent and experience from these applications provide very good data for improving protection design.

Proper protective relay behavior is of key importance to minimize system degradation and to stabilize the system as quickly as possible. Incorrect relay response during frequency excursions is bound to aggravate an already deteriorating situation.

This paper describes how conventional distance protections are affected by frequency variations and how digital technology allows designing reliable protective relays that will behave correctly under such conditions.

Real cases are used for illustration, showing distance protection operations without any provisions for frequency changes. The cases are reevaluated with the same distance protection after adding adaptive algorithms to track system frequency.

The paper includes a description of the problems encountered when implementing the adaptive frequency tracking algorithms and the solutions chosen to ensure reliability independent of system conditions.

Introduction

Frequency variations occur due to imbalance between generated and consumed power. This situation may be caused by:

- Variations in load demand or power generated: An overload of the system caused by excessive load and insufficient generation results in a decline in system frequency while disconnection of loads will increase the frequency.
- Power system faults or line switching: A redistribution of load flow by re-routing produces changes in power transfer between different portions of the system or between interconnected systems which result in frequency fluctuations until a new equilibrium is established between generation and load.

The magnitude and duration of frequency variations depend on the level of imbalance between generated and consumed power and the response to this imbalance by the generators (inertia of the rotating machines and generation control systems). If the frequency excursion is caused by a fault, the duration of the frequency variation is a direct function of how long it takes for the fault to be cleared.

Frequency variations can endanger system stability and may cause damage to generators and, in particular, damage of steam turbines. Frequency below nominal frequency produces, at nominal voltage, over-excitation of generators with severe heating as a result. In addition, when reducing the turbine's rotating speed the frequency may approach the resonant frequency of the rotor blades and cause serious blade fatigue. The effect is cumulative so that the problem is exacerbated every time the turbine is subjected to an under-frequency situation. It is also important to note that low frequency could cause the power plant auxiliaries systems to trip out by reduced pump outputs and fan speeds with the result of having to take the generator station off line.

Generators are provided with regulation systems to correct any load-generation imbalance that may occur. All generators driven by turbines include a turbine governor (primary regulation) which changes the flow (of steam, water or fuel) that enters the turbine when the speed is no longer in synchronism with the system. The control slows down the frequency excursions by correcting imbalances between generation and demand, in case they are not excessive. However, while the primary frequency regulation may stop the excursion, it does not return the frequency to its nominal value. To achieve the last goal there is another control (Automatic Generator Control), which operates on a global level and is active over large areas of generation but with a longer reaction time.

When there is sufficient spinning reserve, a sudden increase in load demand can be compensated for via the regulating methods for generators previously mentioned. However, if the available generation has reached its maximum, the frequency will start to decline. In this case, it is necessary to initiate a selective disconnection of loads (load shedding) with the object of restoring the frequency to normal levels. Carrying out the load shedding in the required time frame is critical as otherwise a continuing decline of frequency may trigger the generator under-frequency relays and making the problem worse. In regions with lack of generation interconnection of grids is of great importance as it allows use of spinning reserves in a neighboring system.

If the generator control systems and system control load shedding operate as intended, the frequency can be maintained within the established margins. However, the reaction time of these systems may not be sufficiently short to handle large generation/load imbalances caused by loss of large blocks of generation or trip of an important tie line with severe frequency variations as a result.

Power systems lacking strong interconnections and without sufficient spinning reserves are likely to suffer frequency excursions. In addition, frequent defects or failures (or inadequate programming: which could increase reaction time) of the regulating control systems these systems often exhibit frequency variations far above admissible levels. This paper has taken into account real cases with frequency deviations larger than 10% from nominal.

Frequency variations have a major impact on protective relay response, especially for distance relays as will be discussed in detail in this paper. Frequency variations occur during stressed system conditions and it is critical that protective relays remain fully operational as the power system is very vulnerable to further disturbances at this time. Both loss of security (undesired tripping) and loss of dependability (no trip) could aggravate the situation. An undesired trip during a frequency excursion is counterproductive to the operational strategy to correct the problem. On the other hand, excessive restraint resulting in lack of tripping for a fault that caused the excursion or for a fault that occurs during the excursion, will further aggravate the situation.

Influence of Frequency Variations on Relay Measurement

Frequency variations in the power system with respect to nominal frequency produce errors in Fourier filter (DFT) calculations as the samples used no longer equal exactly one cycle. Figure 1 and Figure 2 show the resulting magnitudes and phase angles for phase voltages calculated at 48 Hz for a Fourier filter designed for a sampling frequency synchronized to 50 Hz. As it can be seen, there is a ripple in both magnitudes and angles. All the angles represented are relative to VR (phase A voltage). If they were shown as absolute angles, they would have a slope added apart from the ripple, directly related to the frequency variation.

If the system frequency differs greatly from the nominal frequency, the calculation from a filter without frequency tracking can result in considerable errors in the relay measurement.

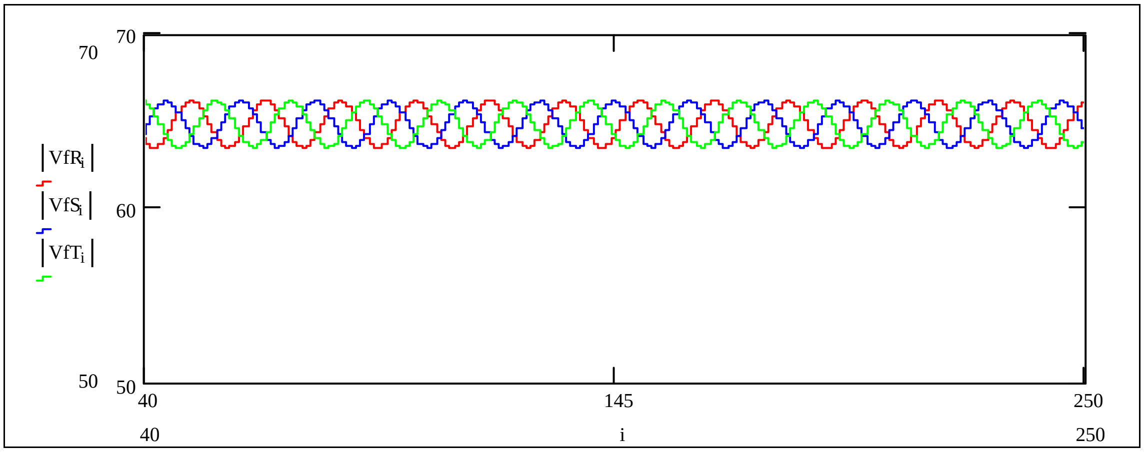

Figure 1. Phase Voltage Magnitudes for a 48 Hz signal (nominal frequency 50 Hz)

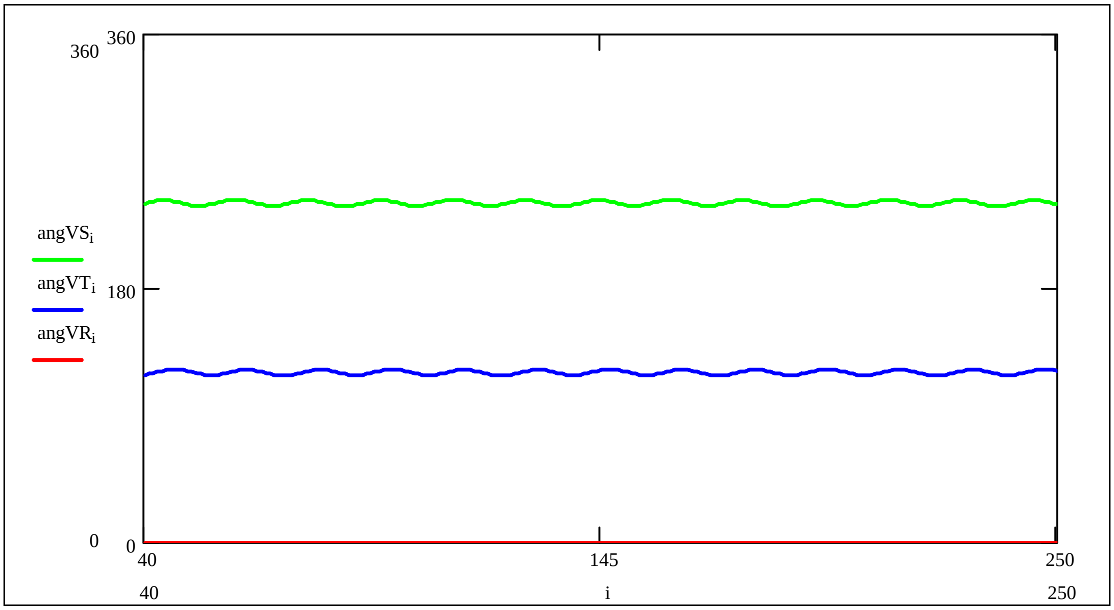

Figure 2. Phase Voltage Angles for a 48 Hz Signal (nominal frequency 50 Hz)

Influence of Frequency Variations on Distance Relays

Distance relay measuring algorithms perform comparison of phasors derived from voltages and currents and settings related to the protected line. Frequency deviation from nominal frequency produces errors in the calculations used for measurement and may cause undesired tripping of the relay. Figure 3 is illustrating the apparent impedance of a 3-phase fault (or load) seen by a distance relay at 48 Hz frequency on a 50 Hz system. The impedance locus corresponds to the samples from half a cycle of the signal. As is evident from the illustration, the measured impedance is not constant but varies continuously. The amount of variation increases with increased deviation from nominal frequency.

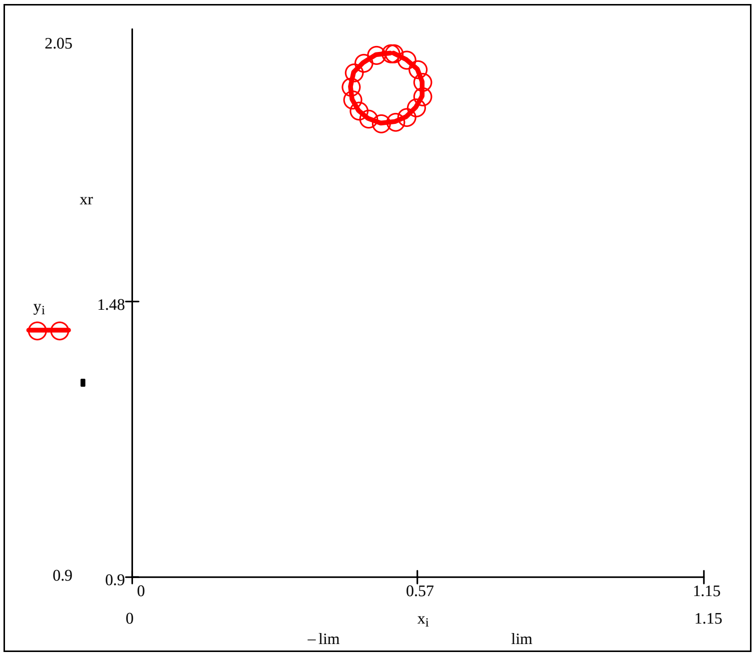

Figure 3. Apparent Impedance for a 3-Phase Fault at 48 Hz as seen by a Distance Relay (nominal frequency 50 Hz)

However, the tendency of a distance relay to misoperate for a frequency variation is not predominantly caused by the previously mentioned impedance calculation errors as they are relatively minor even for a comparatively large frequency deviation. The main cause for undesired tripping is due to the way memory polarization is utilized, as will be discussed below.

Distance relays algorithms generally employ a memorized voltage taken several cycles before the fault inception in order to ensure correct operation for the following conditions:

- Faults with low voltage at the relay terminal, where the polarizing voltage is below the signal threshold required for accurate voltage measurement.
- Faults with voltage inversion on series compensated lines.
- Faults in applications with capacitive voltage transformers (CCVT's) that may generate significant transients, especially for low voltage faults.

The memory times required for the polarizing voltage depend on the type of fault and the system characteristics. We will examine each of the above three cases separately:

Fault with low voltage at the relay terminal, where the polarizing voltage is below the signal threshold required for accurate voltage measurement.

In general, low- or zero-voltage faults occur for faults very close to the relay terminal where there is little line impedance between the relay and the fault location. Close-in faults are located within the relay Zone 1 reach. As Zone 1 trips instantaneously, the polarization memory time required is very short. Typically 2 - 3 cycles' memory is sufficient.

However, in applications with high source-to-line impedance ratio (SIR) the voltage may drop to a very low value also for external faults, beyond the remote line terminal in Zone 2 or even Zone 3. The distance units should remain asserted until the corresponding timer has timed out and it may be necessary to increase polarization memory time up to Zone 2 or Zone 3 time delays.

Faults with voltage inversion on series compensated lines.

Reverse faults on series compensated lines may cause a voltage inversion at the line terminal. In general this happens only for Zone 1 faults as for a fault within Zone 2, the inductive reactance between the voltage transformer and the fault location is larger than the capacitive reactance introduced by the series capacitor. Therefore, the polarizing voltage memory time can be comparatively short. However, in case clearing times of reverse faults by adjacent line protections are excessive, memory time might need to be extended to prevent undesired tripping until the relay protecting the faulted line section has tripped.

Faults in applications with capacitive voltage transformers (CCVT's) that may generate significant transients, especially for low voltage faults.

For applications with CCVT's, the voltage polarization memory time should be long enough to last during the subsidence of any transient produced.

The use of longer polarization times presents a serious problem for distance protection in the presence of frequency excursions. A change in frequency will cause a phase angle shift between the frozen memory voltage phasor and the actual voltage phasor. This shift is especially detrimental for distance relay Mho characteristics.

The Mho characteristic is formed by comparison of the angle between an operating quantity and a polarizing quantity:

$$\begin{aligned} OP &= I \cdot Z_n - V \\ POL &= V_M \end{aligned} \tag{1}$$

Where
I = the fault current for the impedance measuring unit (AG, BG, CG, AB, BC, or CA)
V = the fault voltage for the impedance measuring unit (AG, BG, CG, AB, BC, or CA)
V_M = the polarizing memory voltage (AG, BG, CG, AB, BC, or CA)
Z_n = Zone n reach setting

The mho characteristic operates when the angle between the operating quantity and the polarizing quantity is less than 90 degrees:

$$\left| \angle OP - \angle POL \right| \le 90^\circ \tag{2}$$

Figure 4 is showing the phasors and the resulting mho operating characteristic in an impedance plane.

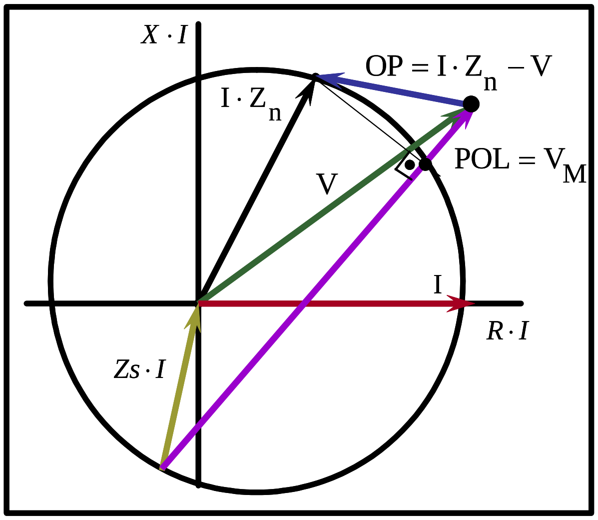

Figure 4. Mho Characteristic

Using the criterion in (2) we will examine the effect of a decrease in frequency on the mho characteristic. The example of the frequency variation used is a real-life event as experienced by a utility in South America on their power system. Figure 5 shows the frequency variations experienced by this utility during one hour time period.

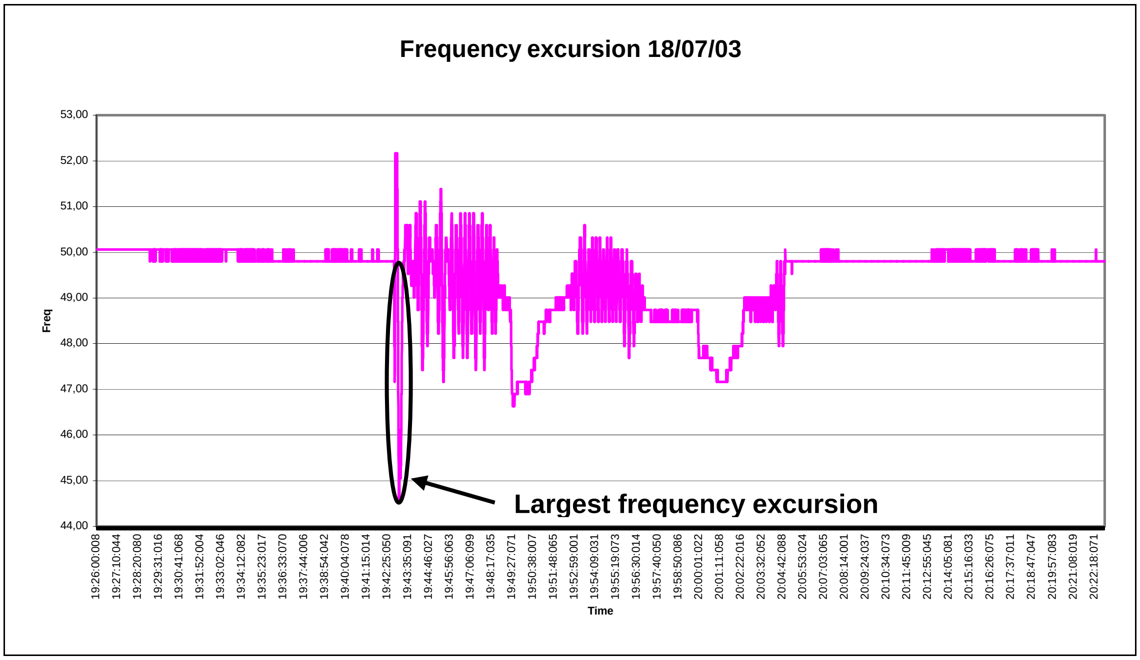

Figure 5. Frequency Variations during One Hour Recorded in a Real Life Event

Figure 6 shows the largest frequency variation over a short period of time. It can be observed that the frequency declines from 50 to 44 Hz in about 3 seconds, giving a rate-of-change of frequency of around -2 Hz/s.

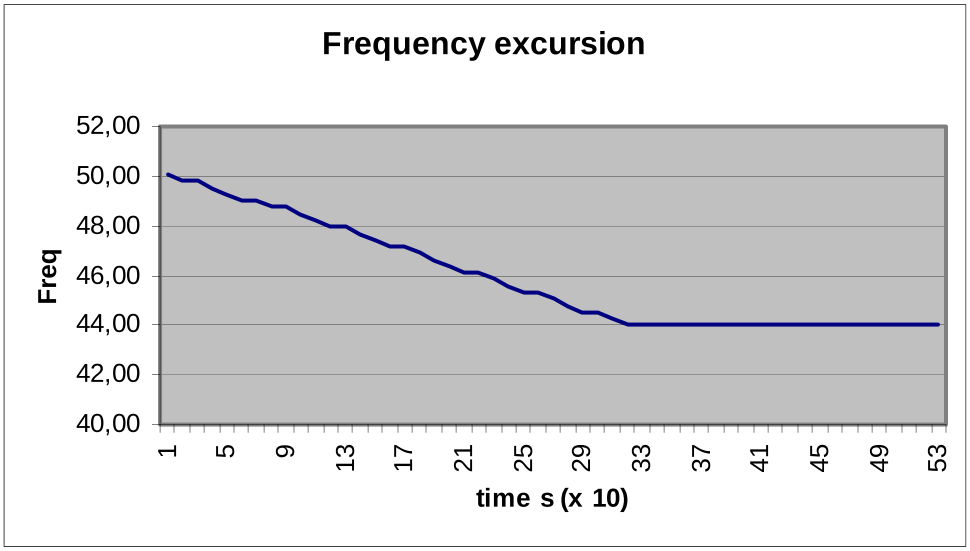

Figure 6. Frequency Variation Recorded in a Real-Life Event

The Zone 1 reach setting was 4 ohms. During the frequency excursion shown above, there was also a decrease in system voltage equal to about 1 V per second, measured on the secondary side of the potential transformer.

Before the frequency excursion occurred, the angle between the operating and polarizing quantity was close to 180 degrees ($\left|\angle OP - \angle POL\right| \approx 180^\circ$) and consequently, the apparent impedance was far outside the mho operating characteristic. However, the frequency excursion produced a shift of the memory voltage phasor with respect to the actual voltage phasor as can be seen in Figure 7. This shift caused a decrease of the angle between the operating and polarizing phasor and in Figure 8 it can be observed that after about 450 ms, the angle approached the 90 degrees required to fulfill the trip criterion.

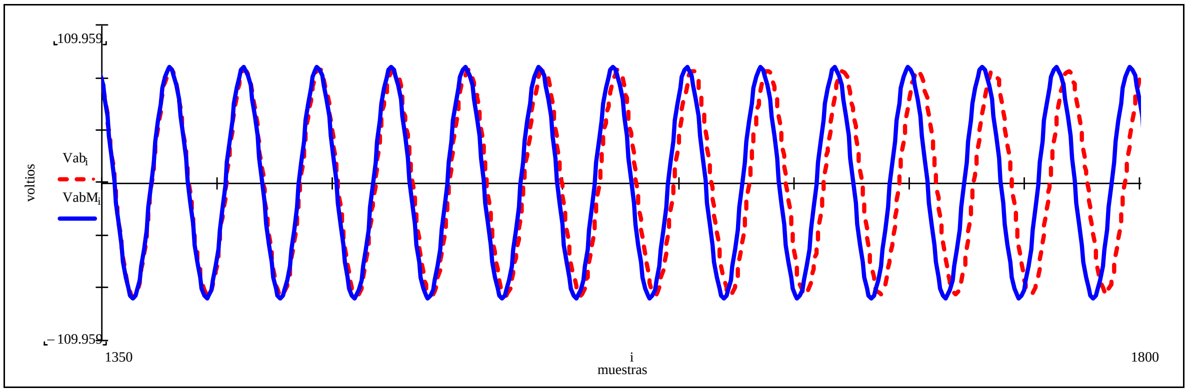

Figure 7. Phase-Phase Memory Voltage (VabM) and Phase-Phase Fault Voltage (Vab)

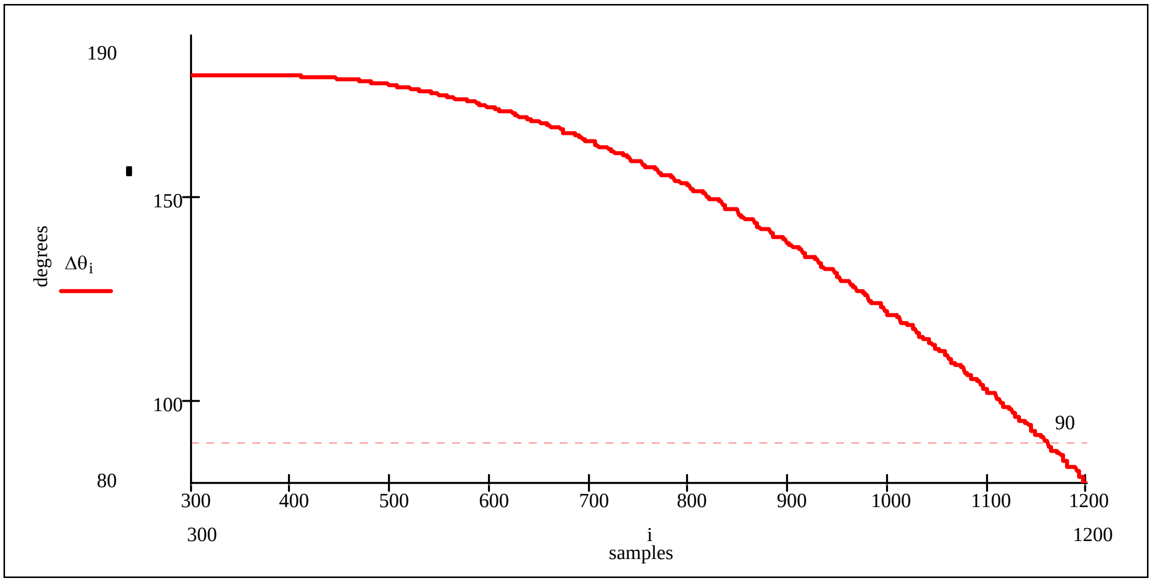

Figure 8. Change in Phase Angle Difference between Operating and Polarizing Phasors during the Frequency Excursion

Consequently, even though there is no fault on the line (or external to the line) the use of very long polarizing memory time can cause undesired tripping by a distance relay mho characteristic during frequency excursion conditions.

The results obtained above for non-faulted conditions are also valid for a system under fault conditions; the mho elements tend to overreach for decreased frequency and underreach for increased frequency.

It is important to note that the tendency for a false operation by the mho characteristic does not only occur while the frequency varies with time but also for any discrete change, because in both cases there is a shift between the polarizing and operating phasors, although the shift is constant in the latter case, instead of varying with time.

For distance relay quadrilateral characteristic, the use of memory voltage is not as prone to cause misoperations during to frequency excursions as for the mho elements. The reason for this is that the memory voltage is used for directional measurement only, and not for reach. It is possible that a large frequency variation could cause loss-of-directionality of the quadrilateral characteristic, but undesired tripping would still not occur as the apparent impedance would be outside the set reactive and resistive reach. However it could result in a missed trip for a forward fault if the directional element sees it in the reverse direction.

We can with simple means implement logic to restrain the use of memory voltage (at least for longer durations) during certain situations:

- The memory voltage should be used only during fault conditions to prevent possible misoperations under normal conditions when no fault is present. The memory voltage is therefore supervised by fault detectors and will not be used unless a sensitive fault detector has picked up.
- The memory voltage could be used only when the available voltage has dropped to a level so low that is it not useful for measurement. As this voltage level needs to be higher when CCVTs are used due to the transients produced, a settable threshold for minimum voltage level is introduced. Also for series compensated lines where voltage inversions can occur for relatively high fault voltages, the threshold needs to be set higher.

However, there is still a need to use memory voltage for 3-phase faults with low terminal voltage and faults with voltage inversion on series compensated lines. If these faults happen during a frequency excursion, an undesired trip could occur. Only by controlling the memory voltage with a frequency tracking algorithm can this risk be eliminated.

Frequency Tracking Algorithm

The errors that are caused by the difference in frequency of the power system with regards to the sampling frequency can be eliminated by an algorithm with adaptable sampling frequency. Instead of using a sampling rate tied to a fixed frequency (50 or 60 Hz), the sampling is adjusted so the number of samples per cycle is fixed for a variable frequency.

The developed algorithm calculates the power system frequency by measuring the cycle (the inverse of frequency) from the waveforms of the three phase voltages. The measurement is using phase A voltage, as long as this voltage is above a certain threshold. If the voltage drops below the predefined threshold, the algorithm can use phase B or phase C voltages but only if they are above the threshold. The use of all three phase voltages for measurement ensures correct frequency tracking as long as one or two voltages are above the threshold, for instance during single pole reclosing dead time. The adaptable voltage measurement also enables use of the tracking algorithm for Zone 2 or Zone 3 single or phase-phase faults in a stepped distance scheme with long fault clearing times.

In order to consider a change of frequency (length of power cycle) to update the frequency presently used for sampling, it is necessary to detect a minimum change over a period of four zero crossings. This also ensures that the frequency measurement is not confused by a sudden change of phase angle. When a change is detected, the sampling frequency is modified to match the frequency based on the last zero crossing of the measured voltage waveform.

As shown in Figure 9, the criterion used to update the sampling frequency is:

$$\left|T0-T1\right| > threshold \cdot \left|T0-T2\right| > threshold \cdot \left|T0-T3\right| > threshold \cdot \left|T0-T4\right| > threshold \qquad (3)$$

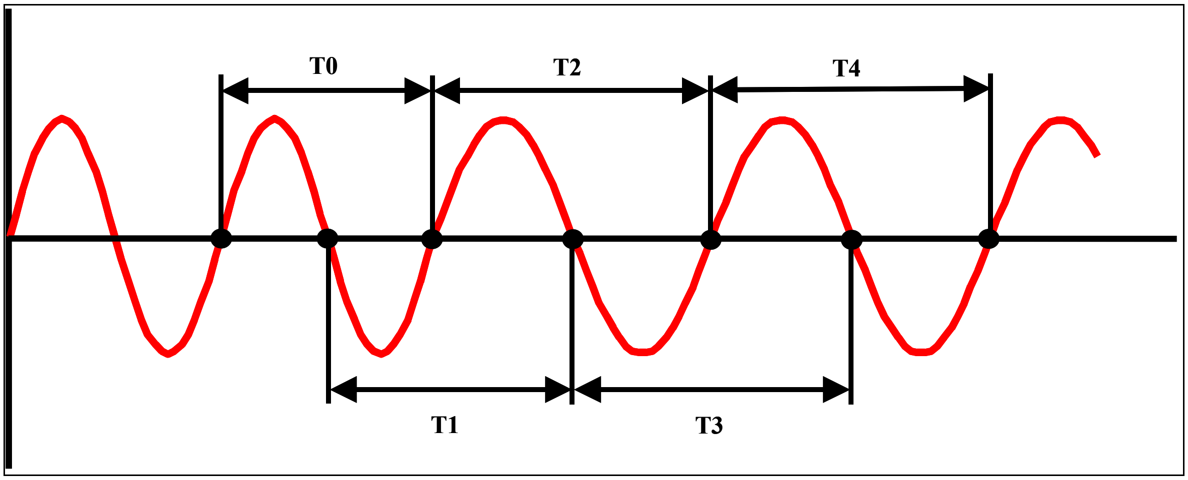

Figure 9. Increased Cycle Time for a Decrease in Frequency

A waveform as shown in Figure 10 does not result in a change of the sampling frequency as |T0 – T3| is smaller than the threshold and the update criterion is not fulfilled.

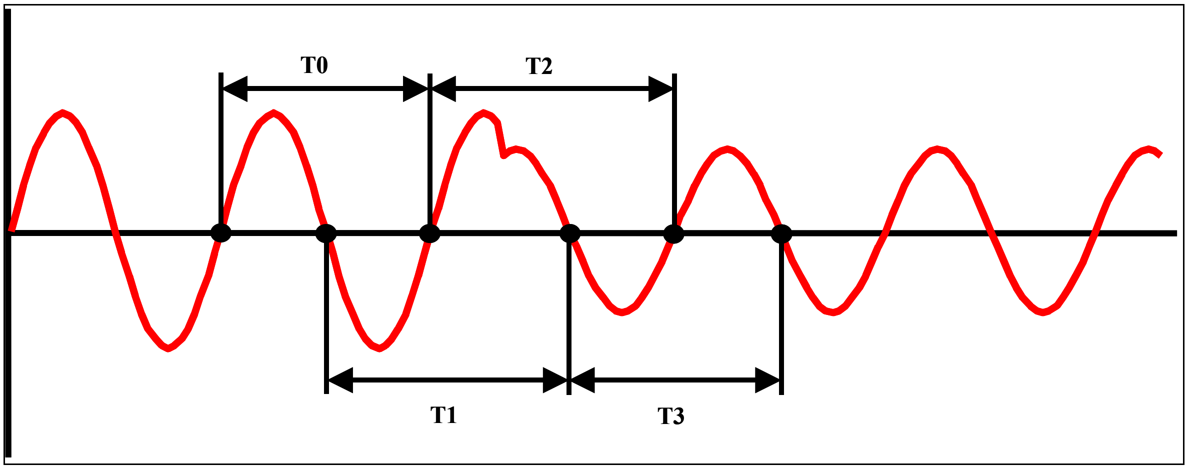

Figure 10. Increased Cycle Time Caused by a Phase Shift during a Fault Condition

When the sampling frequency has adapted to actual system frequency, any measuring errors are eliminated and the polarizing memory voltage is synchronized to actual frequency. However, as the update is delayed by the time it takes for the voltage to make four zero crossings, the shift is again increasing if the frequency variation continues. Nevertheless, the frequency variation during a time period of two cycles (four zero crossings) is very small and any resulting measuring errors and effect on the distance units from the shift in polarizing memory voltage are negligible.

Figure 11 is showing the developing shift in phase angle between the operating and polarizing phasors for the same frequency excursion applied in Figure 8. This time, there is a very small change in the phase angle between the phasors due to the adaptive algorithm that corrects the sampling frequency to match actual system frequency. While there is still a slight reduction of the angle from the initial 180 degrees, the shift is nowhere near the operating threshold of 90 degrees shown by the dashed line.

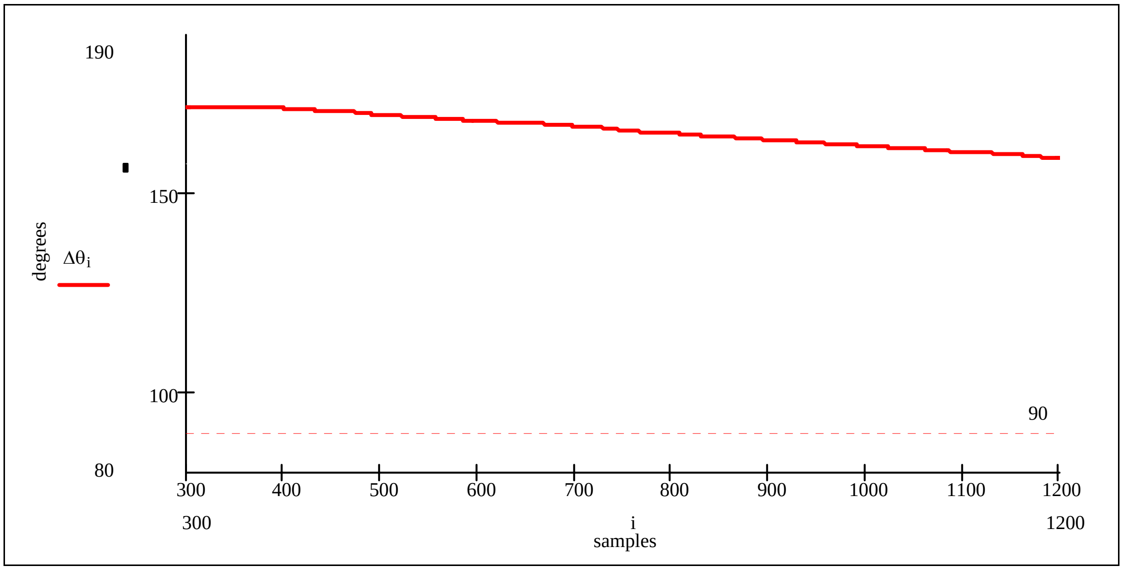

Figure 11. Phase Angle between Operating (OP) and Polarizing Phasors (POL) with Frequency Tracking Algorithm

However, during a prolonged frequency excursion and using long polarizing memory time, there could still be a risk of entering into the operating area. To overcome this problem, the frequency tracking algorithm is also adjusting the memory voltage phasor. Every time the sampling frequency is corrected, the memory voltage phasor is shifted by an angle equal to the shift accumulated during the four zero crossings previously discussed.

As illustrated in Figure 12, the resulting phase angle shift can be determined by calculating the time ΔT by comparing the zero crossings between the initial signal (solid line) and the signal with decreasing frequency (dashed line):

$$\Delta T = \left| 2 \cdot T0 - (T2 + T4) \right| \tag{4}$$

This time shift equals a phase angle shift of:

$$\Delta \alpha = \Delta T \cdot \frac{360}{T0} \tag{5}$$

The frequency is adjusted to the cycle time measured at T4 every two cycles (four zero crossings). At this time, the phase shift between the two waveforms (the solid and the dashed line) is eliminated and the signals are returned to the initial stage. The phase of memory phasor is continuously adjusted to correspond to actual system frequency during frequency excursions, eliminating any risk of undesired operation of a distance relay mho element.

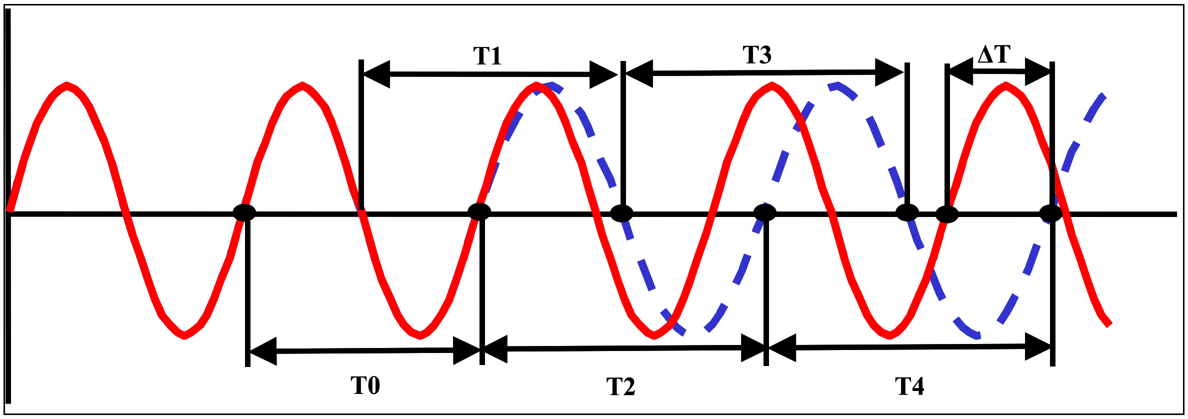

Figure 12. Variation between Voltages of Different Frequency during a Period of Four Zero Crossings

Figure 13 is showing the developing shift in phase angle between the operating and polarizing phasors for the same frequency excursion applied in Figure 8, now with frequency tracking and phase of memory phasor correction. As can be seen, the shift is practically non-existent.

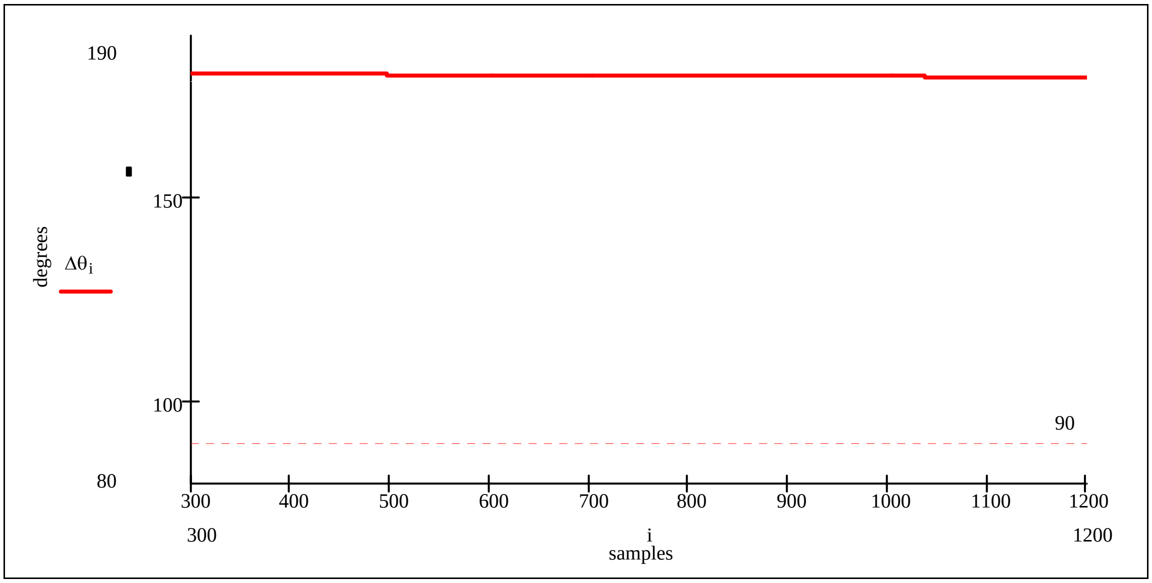

Figure 13. Phase Angle between Operating (OP) and Polarizing Phasors (POL) with Frequency Tracking Algorithm and Memory Voltage Compensation

The algorithm described is compensating for a phase shift between a memorized quantity and the actual measured signal caused by frequency variations. While the distance relay is using the algorithm for memory voltage, it is valid for any memorized signal and does not have to be a voltage. Other application may include situations where measurement is based on pre-fault quantities in order to eliminate influence of load for reactance measurement or phase selector operation. Frequency excursions can also introduce errors in these measurements (underreach or overreach) that can be eliminated by applying this same algorithm.

Conclusions

Despite the efforts by the power utilities to control the system frequency to operate very close to the nominal frequency, many systems are subject to frequency excursions during stressed system conditions. Frequency variations can jeopardize system stability and may also cause damage to generators and turbines. Correct performance of protective relays during these conditions is critical in order to mitigate the effects and not to further aggravate the situation. Conventional distance protections have a tendency to misoperate due to frequency variations, mainly due to the phase angle shift between the memorized polarizing phasor and the operating phasor based on actual power frequency. This paper has described an algorithm that efficiently tracks actual system frequency and adjusts measuring phasors accordingly; preventing undesired trips from distance relay mho elements during frequency excursion events.

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[3]

Biography

Roberto Cimadevilla Gonzalez

Roberto Cimadevilla graduated in Electrical Engineering in the Superior Engineering College of Gijón, Spain in 2001. He obtained a master´s degree in “Analysis, simulation and management of electrical power systems” from the University of País Vasco. He worked in Red Eléctrica de España as Protection Relay Engineer for 1 year. He is with ZIV since the beginning of 2003 as Application Engineer mainly focused in distance protections, being application responsible for the development of a new distance relay.

Rafael Quintanilla

Rafael Quintanilla graduated in Electrical Engineering in the Superior Engineering College of Bilbao, Spain in….In 1978 he started working in GE Spain where he held several positions in the field of the design and application of analog and digital equipment and systems applied to protection and control of electrical power systems. He is one of the founders of ZIV, where he currently works as General Manager of the Protection and Control Division. He has written several papers…

Solveig M. Ward

Solveig received her M.S.E.E. from the Royal Institute of Technology, Sweden in 1977. The same year she joined ABB Relays. She has held many positions in Marketing, Application, and Product Management. Assignments include a six-month period in Montreal, Canada and two years in Mexico. When Ms. Ward returned to Sweden, she was application responsible for the development of a numerical distance protection relay and in charge of marketing the product. After transferring to ABB in the US 1992, she was involved in numerical distance protection application design, and was Product Manager for ABB’s line of current differential and phase comparison relays.

Solveig has written, co-authored and presented many technical papers at Protective Relaying Conferences. She is a member of IEEE and holds one patent. In June 2002, Solveig joined RFL Electronics Inc. as Director of Product Marketing