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Fast Ground Directional Overcurrent Protection: Limitations and Solutions

FAST GROUND DIRECTIONAL OVERCURRENT PROTECTION – LIMITATIONS AND SOLUTIONS

Bogdan Kasztenny
Bogdan.Kasztenny@IndSys.GE.com
(905) 201 2199

Dave Sharples*
Dave.Sharples@IndSys.GE.com
(905) 201 2168

Bruce Campbell
Bruce.Campbell@IndSys.GE.com
(905) 201 2027

Marzio Pozzuoli
Marzio.Pozzuoli@IndSys.GE.com
(905) 201 2056

GE Power Management
215 Anderson Avenue
Markham, Ontario
Canada L6E 1B3

* Consultant

1. Introduction

Application of the zero- and negative-sequence currents and voltages to fast ground overcurrent protection brings several advantages (section 2):

- The zero- and negative-sequence currents practically do not contain any load components. The pickup levels for their magnitudes may be set low ensuring sensitive operation. Also, the directional discrimination based on the ground quantities is more accurate as compared to the phase quantities because the load does not affect the zero- and negative-sequence currents.
- As the zero- and negative-sequence currents and voltages build up from very low values (practically from zero) during faults, accurate angular relations between them establish very quickly. This is because their pre-fault values do not bias the developing fault components in any direction. This creates an opportunity for fast operation of protection elements that utilize angular relations between the zero- and negative-sequence currents and voltages such as directional elements or phase selectors.

There are, however, certain limitations to both sensitivity and speed of protection elements based on the zero- and negative-sequence quantities (section 4):

- Spurious zero- and negative-sequence quantities, both currents and voltages, may develop during faults as a result of finite accuracy of the relay measuring chain including input circuitry and digital measuring algorithms of microprocessor-based relays. Unfortunately symmetrical three-phase faults may cause a relay to see spurious zero- and negative-sequence quantities in a transient period.
- When a fault gets cleared the zero- and negative-sequence quantities appear as a result of breaker pole asymmetry. Even a mechanically perfect breaker introduces an "electrical" 60-degree difference between consecutive interruptions of the phase currents (the 60-degree interval may be extended even more if the fault is cleared quickly and dc components are still present in the currents). Mechanical asymmetry of the breaker may only worsen the situation.
- The finite accuracy of instrument transformers, both Current Transformers (CTs) and Capacitive Voltage Transformers (CVTs), may cause significant and long lasting spurious negative- and zero-sequence currents and voltages.

As a consequence of the aforementioned, fast and sensitive ground directional elements present a design challenge. For example, on three-phase symmetrical external faults a false trip signal may be generated; or on three-phase symmetrical internal faults a false block signal may be issued.

This paper addresses the aforementioned issues in detail (sections 3 and 4).

In the paper, two solutions to the challenge of fast and robust ground directional protection in the presence of spurious zero- and negative-sequence quantities have been presented (section 5) in detail and illustrated by examples (section 6). They include an energy-based directional comparator and positive sequence restraint.

2. Application of Ground Overcurrent Protection

Ground directional overcurrent protection has been widely applied by utility application engineers, predominantly because information with respect to the direction of the fault current is of significant assistance in achieving optimum settings and time coordination. Irrespective of the design approach used, it is generally accepted that the concept of ”torque” control is the most secure approach for a directional overcurrent element.

The source of polarization for a directional element however should be approached with caution. Zero sequence voltage, at least for some, is the most likely choice. It is useful to perform some analysis to decide whether the inter-circuit mutual effects, especially from lower voltage circuits, can be a problem. When this situation exists, negative sequence may well be the preferred choice for a polarizing signal.

In order to provide the required flexibility modern protective relays may offer a choice of matching:

- The negative-sequence- or zero-sequence-based overcurrent function with
- The choice of either negative-sequence- or zero-sequence-based directional function.

Current polarization has its own problems, specifically the current in the neutral to ground connections in a wye-delta-wye or an autotransformer can exhibit an indeterminate direction. The solution for the wye-delta-wye case is to use the summation of CTs in both neutral to ground connections, the CT ratios being chosen to give an approximation to the delta tertiary current. Similarly the neutral to ground connection of an autotransformer may not be an appropriate choice, and again the tertiary current is the most reliable source of a polarizing signal.

In order to provide flexibility modern protective relays may offer a choice with respect to polarization of ground overcurrent direction functions:

- Voltage polarization,
- Current polarization,
- Dual polarization.

Pilot schemes using distance relays have inherently limited fault resistance coverage. A ground directional overcurrent protection using either negative- or zero-sequence can be a useful supplement to give more coverage for the high resistance fault situation. However, because of the extremely large “effective reach” of a ground directional element, the current reversal situation still requires attention, if a secure implementation is to be achieved.

To achieve sensitive settings, consideration must be given to the likely unbalance, under normal (no-fault) conditions, that may produce both zero- and negative-sequence quantities.

3. Digital Estimation of Symmetrical Components

The concept of symmetrical components has been historically introduced for suitable representation of three-phase networks and analysis of asymmetrical events such as faults and open conductor conditions in steady states.

Mathematically, the three phase quantities, say voltages, get represented by another three quantities, called symmetrical components, calculated according to the well-known linear transformation:

- For the ABC system rotation with the line-to-neutral voltages available:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (1)$$

- For the ACB system rotation with the line-to-neutral voltages available:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (2)$$

- For the ABC system rotation with the line-to-line voltages available:

$$\begin{bmatrix} \bullet \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} \bullet & \bullet & \bullet \\ b & b \cdot a & b \cdot a^2 \\ b^* & b^* \cdot a^2 & b^* \cdot a \end{bmatrix} \cdot \begin{bmatrix} V_{AB} \\ V_{BC} \\ V_{CA} \end{bmatrix} \quad (3)$$

- For the ACB system rotation with the line-to-line voltages available:

$$\begin{bmatrix} \bullet \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} \bullet & \bullet & \bullet \\ b & b \cdot a^2 & b \cdot a \\ b^* & b^* \cdot a & b^* \cdot a^2 \end{bmatrix} \cdot \begin{bmatrix} V_{AB} \\ V_{BC} \\ V_{CA} \end{bmatrix} \quad (4)$$

where: $a = 1\angle 120^0$, $b = \frac{1}{\sqrt{3}}\angle 30^0$ and $b^* = \frac{1}{\sqrt{3}}\angle -30^0$.

In (1)-(4) all the signals are phasors reinforcing accurate application of symmetrical components to steady-state sinusoidal signals.

Application of symmetrical components for fast protective relaying creates some theoretical problems of understanding what “transient symmetrical components” are.

Only the definition of the zero-sequence component can be extended for instantaneous values (samples in a microprocessor-based relay). The positive- and negative-sequence components do not have an instantaneous form. It is worth noting that some other transformations (i.e. methods of representing a three phase system in other than “natural” coordinates) such as the Clarke transformation do apply to both instantaneous values and phasors but they are not suitable for power system protection.

Historically only the symmetrical quantities have been used in protective relaying and the relays measure the symmetrical components accordingly.

In both analog and digital worlds, the circuits (analog) and algorithms (digital) are derived by blind replication of the steady-state definition (1)-(4) of symmetrical components.

Digital relays can measure the symmetrical components following either of the two methods:

(a) "Phasor Estimator + Phase Shifter" approach estimates the phasors of phase signals first and combines them into symmetrical components using equations (1)-(4), accordingly.

(b) "Phase Shifter + Phasor Estimator" approach shifts the signals in the time domain first, and then estimates the phasors. This approach may give a false impression of "instantaneous symmetrical components" as the phase shifting operation may look like the following:

$$v_{0(t)} = \frac{1}{3}\left(v_{A(t)} + v_{B(t)} + v_{C(t)}\right) \tag{5}$$

$$v_{1(t)} = \frac{1}{3}\left(v_{A(t)} + v_{B(t-\frac{2}{3}T)} + v_{C(t-\frac{1}{3}T)}\right), \text{ or } \quad v_{1(t)} = \frac{1}{3}\left(v_{A(t)} - v_{B(t-\frac{1}{6}T)} + v_{C(t-\frac{1}{3}T)}\right) \tag{6}$$

$$v_{2(t)} = \frac{1}{3}\left(v_{A(t)} + v_{B(t-\frac{1}{3}T)} + v_{C(t-\frac{2}{3}T)}\right), \text{ or } \quad v_{2(t)} = \frac{1}{3}\left(v_{A(t)} + v_{B(t-\frac{1}{3}T)} - v_{C(t-\frac{1}{6}T)}\right) \tag{7}$$

where t is time, T is the fundamental frequency period, while the signals are instantaneous values.

As both the phasor estimation and phase shifting are linear operations, their order in the signal processing chain does not matter.

Both the approaches (a) and (b) will exhibit natural transient errors more due to the lack of meaning of symmetrical components during transients than due to the transients themselves.

By transients we mean here both transient components superimposed on the sinusoidal signals as well as the effect of the sliding data windows of digital measuring algorithms.

The latter alone can generate spurious symmetrical components. However, it is not due to any inherent imperfections of digital algorithms: the moving data windows are just equivalents of the internal energy of circuits used for filtering in the analog world. Until a circuit (or an algorithm) settles (reaches its steady state), the symmetrical components are not defined, and as such, can not be reliably measured.

This fact is often overlooked. The next section illustrates and explains some of the situations creating spurious symmetrical components.

4. Spurious Symmetrical Components

By a spurious symmetrical component we mean the situation of normally unexpected – and typically non-zero – value of the component, such as negative-sequence current during three-phase symmetrical faults. The following causes of spurious symmetrical components are discussed:

- Transient estimation errors
- CT errors and saturation
- VT errors and CVT transients

4.1. Transient Estimation Errors

One type of spurious symmetrical components observed during fault conditions may be entirely contributed to transient estimation errors.

Consider for example, a perfectly symmetrical three-phase fault occurring during perfectly symmetrical load conditions. As a symmetrical set of phase currents develops into another symmetrical set of currents, one would not expect any negative- nor zero-sequence symmetrical components. They may, however, appear because the phasor estimators – such as the Fourier algorithm – have different operating conditions in particular phases.

Fig.1a shows an idealized sinusoidal waveform developing from zero to some finite magnitude at the phase angle φ. This waveform represents only the fundamental frequency component of a fault signal. The actual fault signal contains other components but only the fundamental frequency sinusoidal waveform is critical for this analysis. Depending on the phase angle, the magnitude of the signal estimated using the full-cycle Fourier algorithm changes from zero to the actual magnitude in a different way (Fig.1b). The transition is not longer than the total window length (one cycle) and depends on the phase angle of the signal.

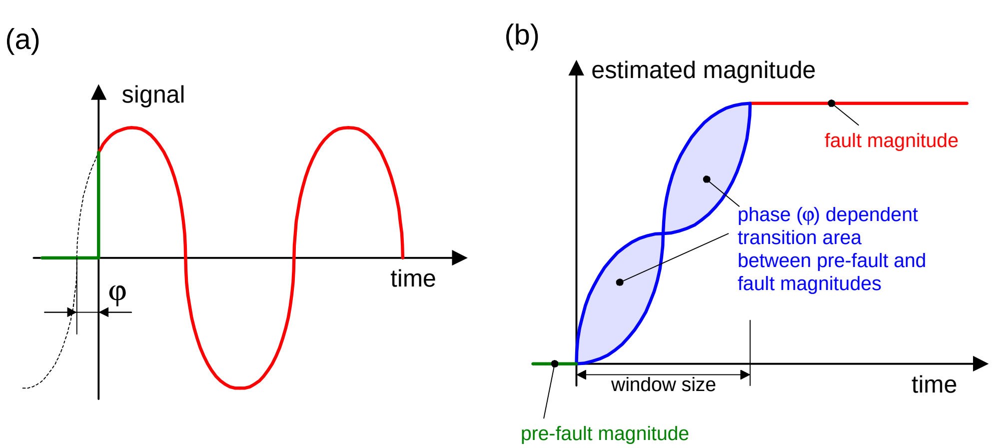

Figure 1. Initial phase angle of the signal developing from a pre-fault magnitude to a fault magnitude (a) causes uncertainty of the transition from the pre-fault to fault values of the estimated signal magnitude (b).

Figs.2-7 illustrate that phenomenon for currents during a sample three-phase symmetrical fault.

As shown in Fig.2 the phase currents have different initial angles at the fault inception resulting in different dc components (In all the following examples the signals are sampled at 64 samples per cycle and the phasors are estimated using the full-cycle Fourier algorithm refreshed 8 times per cycle).

As shown in Fig.3 the three magnitudes representing the A, B and C currents ramp up (fault inception) and down (fault clearance) differently due to different phase angles. During the fault clearance the difference is certainly larger as the breaker pole asymmetry (approximately 60 degrees depending on the existing dc component and mechanical breaker pole asymmetry).

The phase angles of the three phasors will also differ as shown in Fig.4.

Fig.5 zooms-in on the magnitude difference at fault inception: 6 msec into the fault, for example, the difference between the two phases and the remaining one is more than 50%. From Fig.6, which represents the developing phasors and using the same 6-msec time mark for illustration, it is quite obvious that the transient period is not symmetrical.

Fig.7 plots the magnitudes of the positive-, zero- and negative-sequence components.

The following summarizes the situation:

- Spurious negative-sequence component appears on both fault inception and clearing (even by a mechanically perfect breaker). The spurious values last for the duration equivalent to the total window length (pre-filter + Fourier) and may reach some 25% of the actual positive-sequence component.
- Spurious zero-sequence component appears on fault clearing only and is substantially lower (some 10% for a mechanically perfect breaker).
- The phase angles of spurious symmetrical components are chaotic.
- If the fault clearing involves substantial pole asymmetry, the symmetrical quantities appear naturally, are no longer "spurious", their magnitudes result from double-phase or single-phase operation of a three-phase circuit, and their phase angles are no longer chaotic but reflect the actual fault direction.
- Similar concussions apply to line-to-line faults and the zero-sequence current.

An ideal solution to these kind of transient measuring errors is to design a phasor estimator that would ensure:

- same ramp-up / ramp-down rate for the magnitude and
- same transition for the angle for all three phase signals.

Practically, this means a phasor estimator having an invariable step response irrespective of the initial phase angle of the signal.

One such estimator uses the following equation to provide – theoretically at least – invariable magnitude step response:

$$X_{(k)} = C \cdot \sqrt{\left| x_{\mathrm{Re}(k)} \cdot x_{\mathrm{Im}(k-m)} - x_{\mathrm{Im}(k)} \cdot x_{\mathrm{Re}(k-m)} \right|} \tag{8}$$

where x_{Re} and x_{Im} are real and imaginary parts of the phasor estimated using any filtering approach, m is a constant delay, k is a sample index, and C is an m-dependent scaling factor.

No good solution is known to make the angle response invariable.

Besides, the step response of (8) is independent from the initial phase angle of the fundamental frequency component. It would be, however, affected by signal distortions making the idea of providing an estimator of an invariable step response less practical.

4.2. CT Errors and Saturation

Transformation errors of CTs (linear mode) will contribute to prevailing, or long lasting as opposite to transient, values of spurious symmetrical components.

Taking into account the defining equation (1), the percentage error, p, in each of the three phases can contribute to not more than p percent of the positive sequence being seen as the spurious negative- or zero-sequence component. This will happen if all three signals are measured with the maximum assumed magnitude error of p and the phase angle of the error signals favor given symmetrical component (for example, all three errors are in phase if the zero-sequence is considered). Practically, the errors will mutually cancel to the some extent, but still one may expect at least a few percent of three-phase current to be seen by a relay as the spurious zero- and/or negative-sequence current.

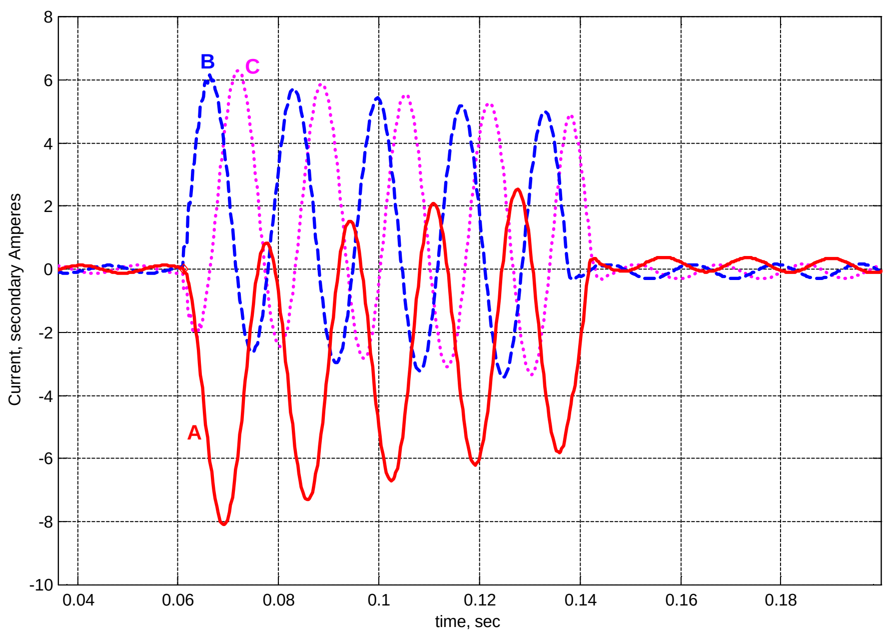

Figure 2. Sample three-phase symmetrical fault: Current Waveforms.
The three phase currents develop from the same pre-fault magnitudes to the same fault magnitudes, but the transition takes place at different initial (fault inception) angles.

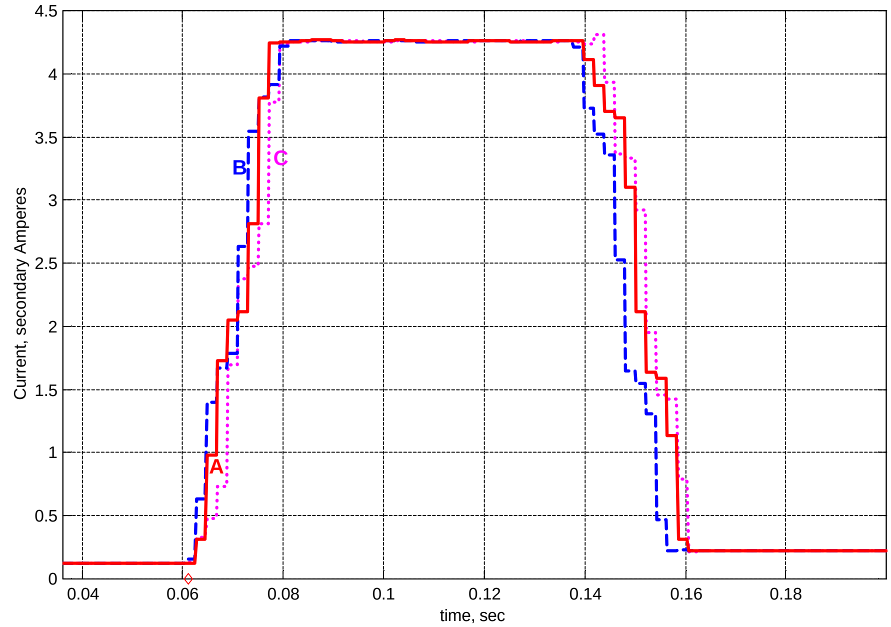

Figure 3. Sample three-phase symmetrical fault: Current Magnitudes. Due to different fault inception angles the three phase currents ramp up (and down when the fault gets cleared) in slightly different ways.

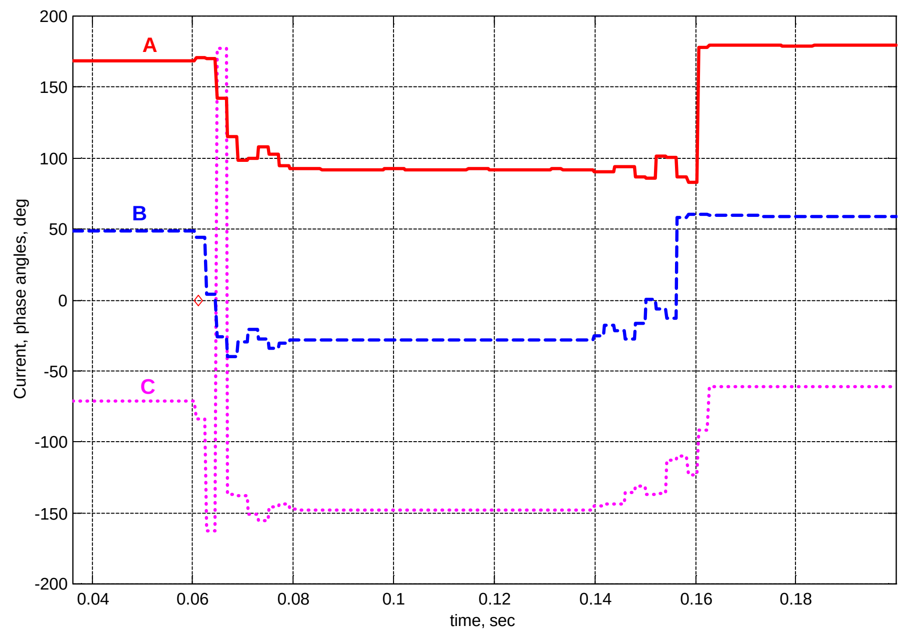

Figure 4. Sample three-phase symmetrical fault: Current Phase Angles. Due to different fault inception angles the three phase currents change their phase angles in slightly different ways.

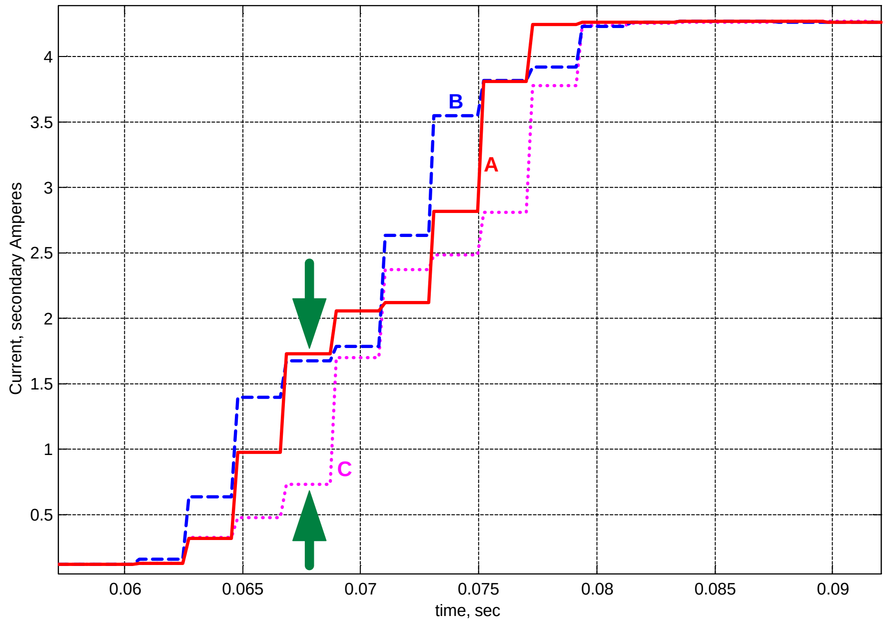

Figure 5. Sample three-phase symmetrical fault: Current Magnitudes. At 6 msec into the fault the magnitude of the phase C current substantially differs from the two other phases.

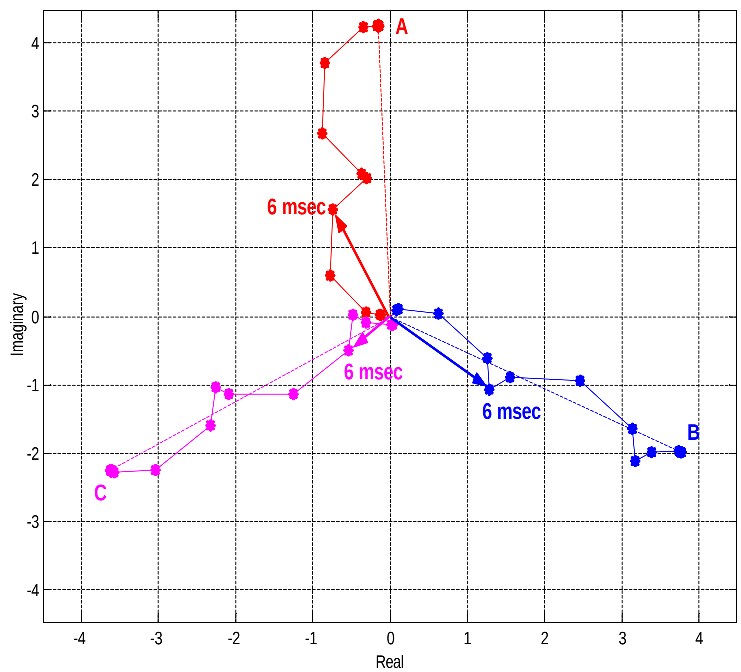

Figure 6. Sample three-phase symmetrical fault: Current ABC Phasors. The dots stand for “protection passes” being 2 msec apart. At 6 msec into the fault the ABC current diagram is unquestionably not symmetrical (the magnitudes are not equal – Fig.5, the phase angles are not 120 degrees apart – Fig.4).

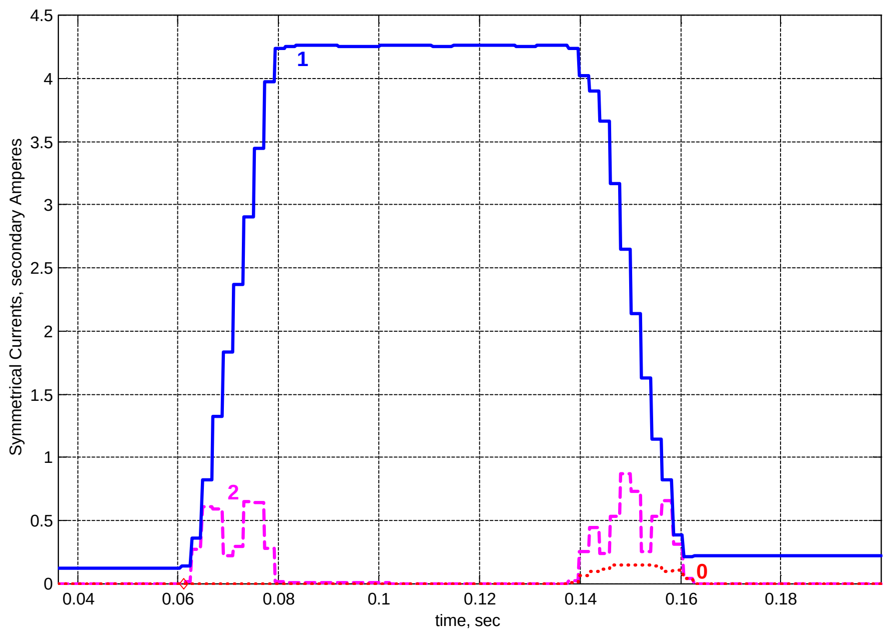

Figure 7. Sample three-phase symmetrical fault: Current Symmetrical Components (012). Spurious negative-sequence current appears on both fault initiation and clearing. Spurious zero-sequence current appears on fault clearing.

Much higher values of spurious symmetrical components occur when the CTs saturate. Figs.8 and 9 illustrate this by showing a sample three-phase symmetrical fault and the measured symmetrical components. The "seen" negative- and zero-sequence currents are as high as 20% of the steady-state positive sequence value.

Fig.9 illustrates also the fact that the positive sequence current can be significantly underestimated due to CT saturation. The underestimation can be much higher for the positive-sequence than for the individual phase currents.

Fig.10 presents yet another example – a wye/delta transformer is energized from the delta side. No zero-sequence current is expected unless the transformer suffers an internal fault. This holds true for primary currents. The secondary currents do not follow that pattern because of the simple fact of CT saturation.

4.3. CVT Transients

CVTs can cause similar phenomena in Extra High Voltage (EHV) networks:

- Linear errors of p percent can contribute to up to p percent of negative- and/or zero-sequence components.
- CVT transients lasting typically two or more power system cycles create extra asymmetry resulting in spurious components of a chaotic phase angle and magnitude reaching some 20% of the nominal voltage. Fault clearing could generate even higher spurious symmetrical components (see Figs.11-14 for illustration).

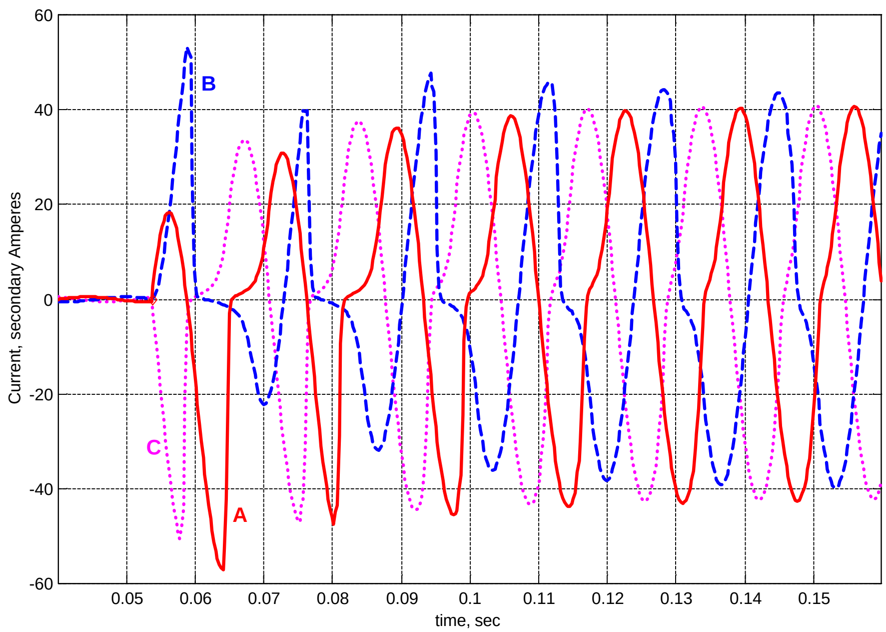

Figure 8. Sample three-phase symmetrical fault with heavy CT saturation: Current Waveforms.

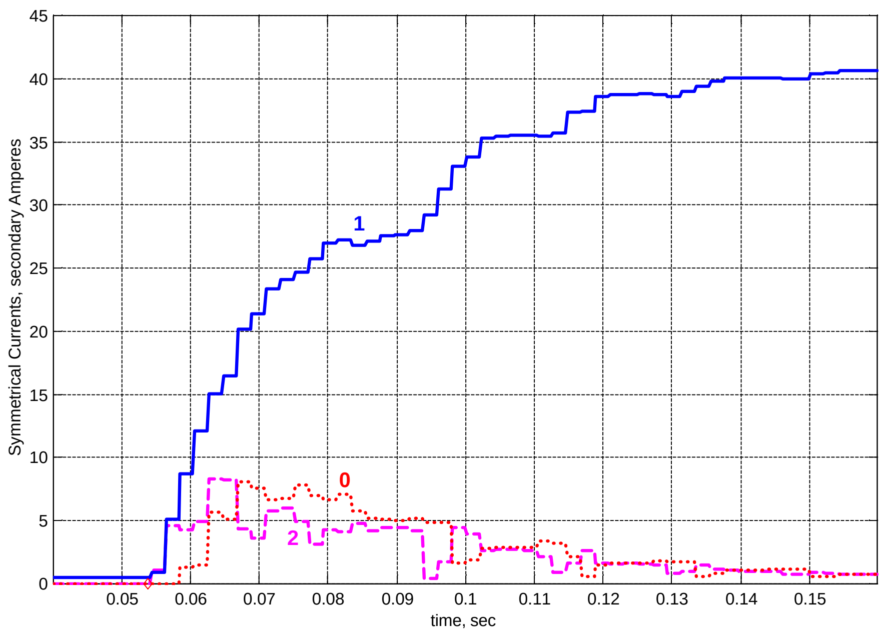

Figure 9. Sample symmetrical fault with heavy CT saturation: Current Symmetrical Components (012). Due to CT saturation spurious negative- and zero-sequence currents appear for considerable time.

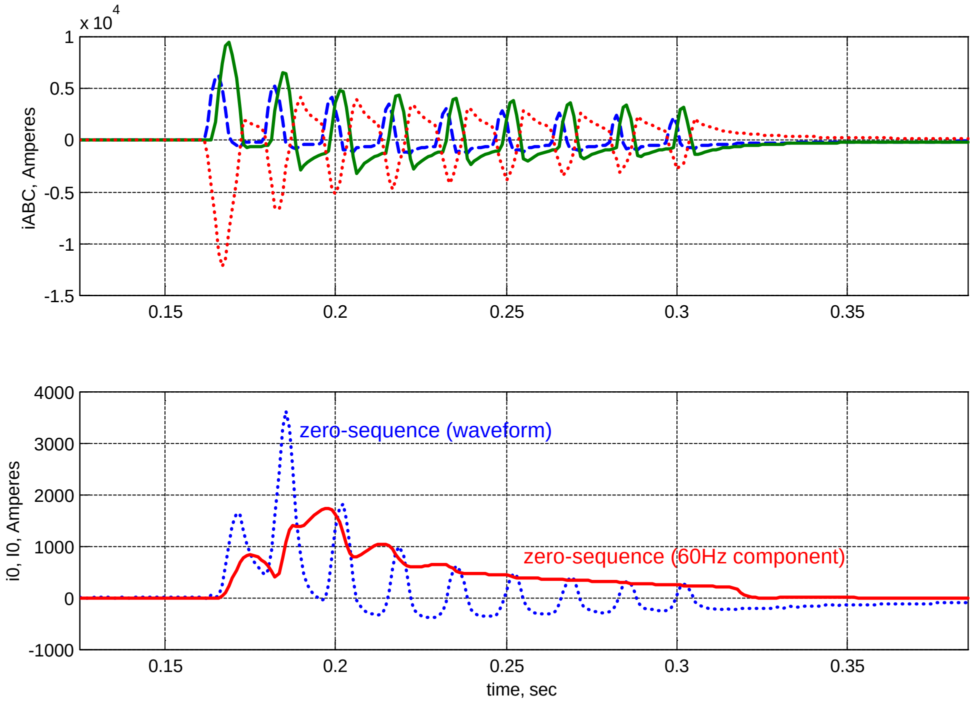

Figure 10. Sample transformer inrush currents. The transformer is energized from its delta winding – no zero-sequence expected. Due to CT saturation (long lasting dc components) spurious zero-sequence current as high as 30% of the inrush current appears.

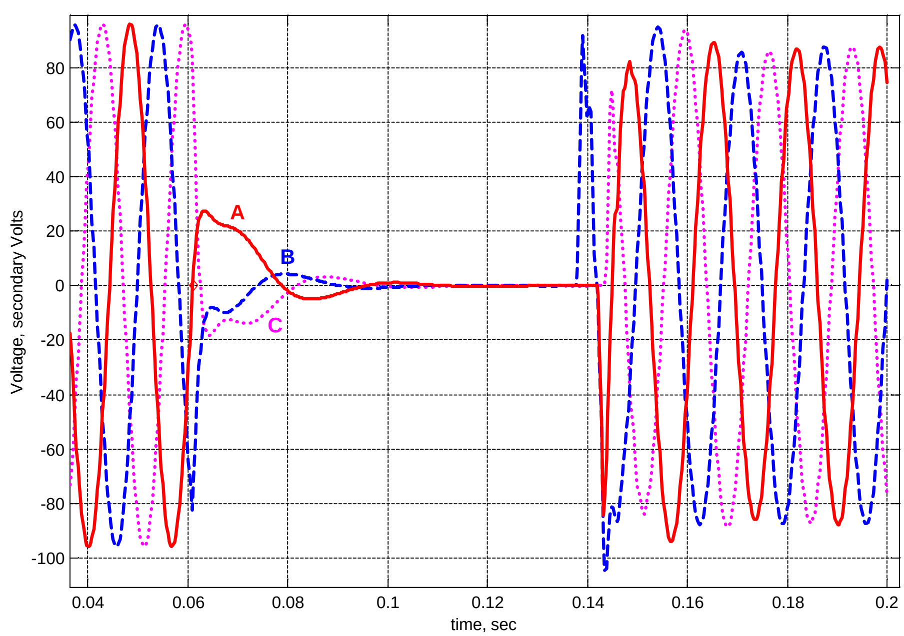

Figure 11. Sample (see Fig.2 for currents) three-phase symmetrical fault: Voltage Waveforms. Due to heavy CVT transients, the three phase voltages behave differently during first 40 msec into the fault.

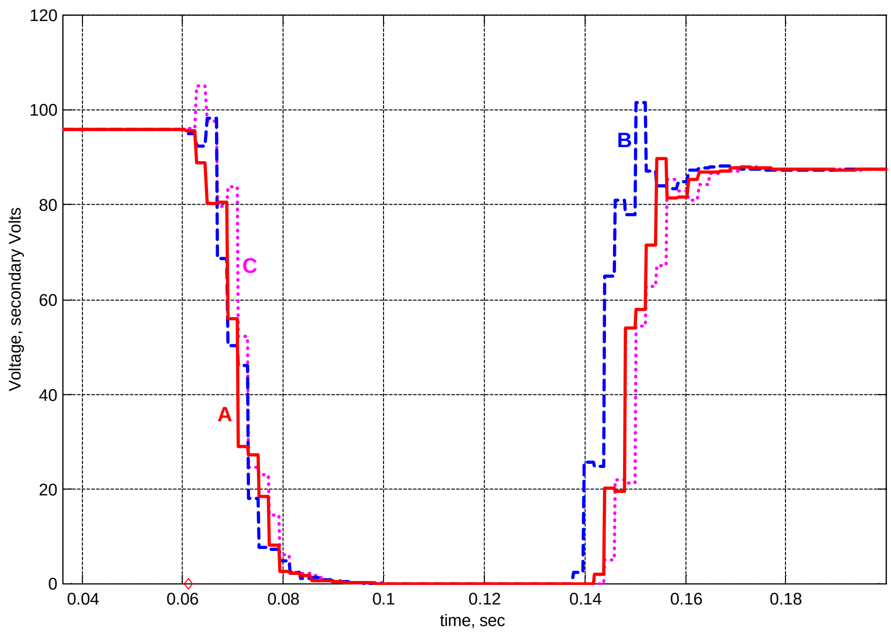

Figure 12. Sample three-phase symmetrical fault: Voltage Magnitudes.

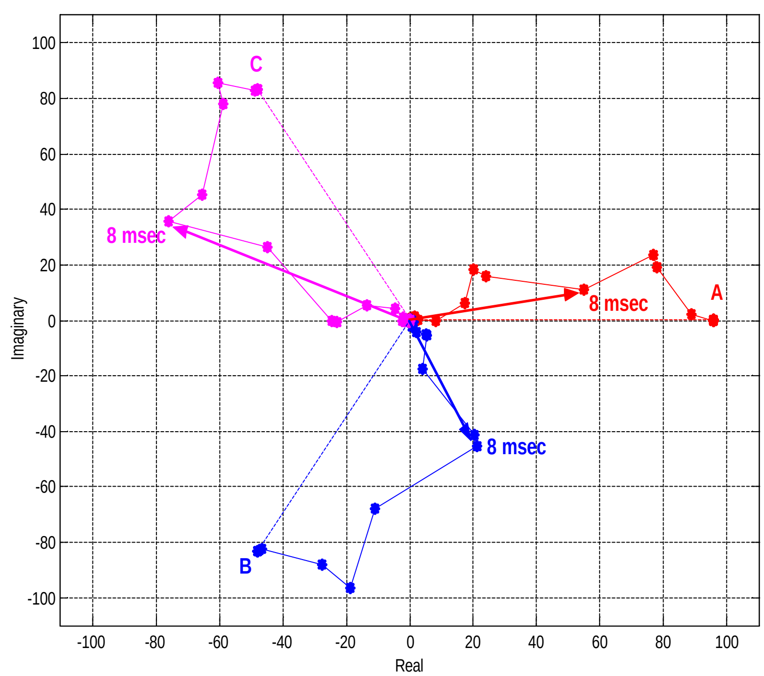

Figure 13. Sample three-phase symmetrical fault: Voltage ABC Phasors. At 8 msec into the fault the ABC voltage diagram is unquestionably not symmetrical.

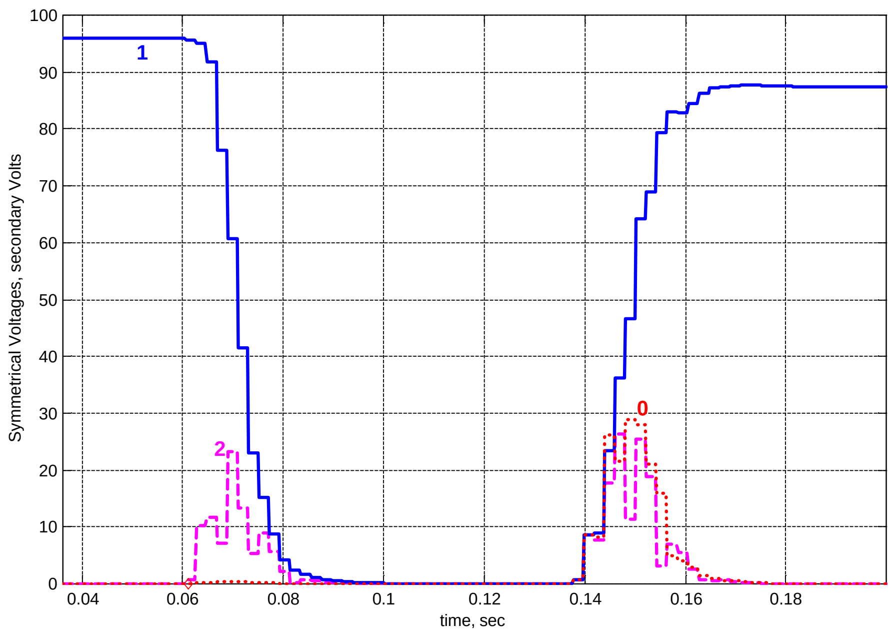

Figure 14. Sample three-phase symmetrical fault: Voltage Symmetrical Components (012). Spurious negative-sequence voltage appears on both fault initiation and clearing. Spurious zero-sequence voltage appears on fault clearing.

Spurious sequence components in both currents and voltages can create problems for fast ground directional overcurrent protection. The magnitude check may falsely validate the signals while their phase relation may randomly satisfy the operating conditions causing malfunction.

5. A Fast Ground Directional Overcurrent Algorithm

With reference to Fig.15 the proposed approach uses a "positive-sequence restraint" to cope with spurious symmetrical components, and an "energy-based directional comparison" in the directional part to cope with angle uncertainty during transients.

5.1. Positive-Sequence Restraint

In order to compensate for small system unbalances and CT/VT/CVT linear transformation errors, as well as to partially cope with transient errors, the concept of positive-sequence restraint can be effectively used. The operating quantity for the overcurrent part of the negative/zero sequence directional overcurrent protection element is compensated with a small portion of the positive-sequence current:

$$I_{op} = I_2 - K \cdot I_1 \qquad (9)$$

This solution is much better than just raising the threshold for a plain zero- or negative-sequence current magnitude. Truly, the system unbalance and the CT/VT/CVT trans-

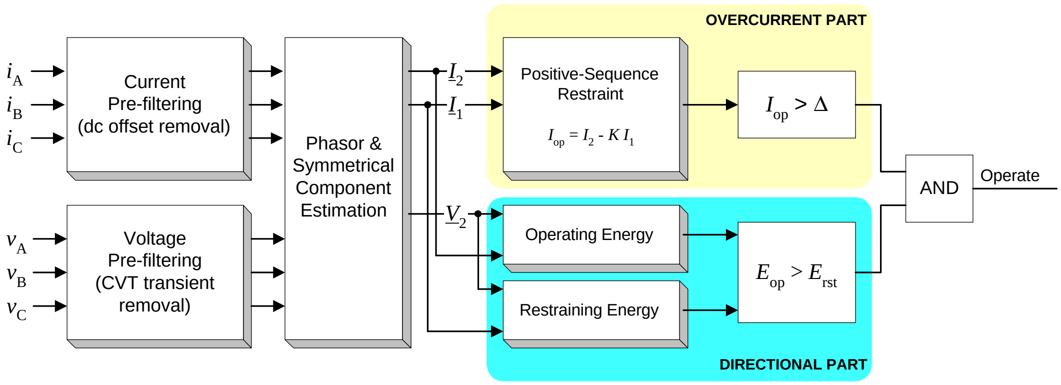

Figure 15. Simplified block diagram of the new algorithm (negative sequence shown).

formation errors are proportional to the positive sequence current and the linear additive compensation (8) is entirely justified.

One particular solution uses the value of K of 1/8th for the negative-sequence and 1/16th for the zero-sequence current.

The positive-sequence restraint being an excellent solution to some sorts of spurious symmetrical components calls, however, for caution during testing.

Imagine two test scenarios:

(a) Single-phase current injection ($I_1 = I_2 = I_0$, $I_{op} = (1 - K)\, I_2$, the negative-sequence IOC set at, for example 1A, will pick-up when 3 • 1.143 A is injected).

(b) Three-phase negative-sequence current injection ($I_1 = I_0 = 0$, $I_{op} = I_2$, the negative-sequence IOC set at, for example 1A, will pick-up when 1.000 A is injected).

Another testing and application misunderstanding may be caused by confusing the terms “ground”, “neutral” and “zero-sequence”. The difference of the factor of 3 may lead to serious misapplications. Microprocessor-based relays measure the symmetrical quantities directly, and for some functions (display and oscillography, for example), may use I_0 instead of $3I_0$.

The same may apply to the protection functions if the negative-sequence and zero-sequence quantities may be selected as per the user’s choice. In order to keep the threshold consistent either I_0 and I_2, or $3I_0$ and $3I_2$ should be used. None of the choices is obvious and self-manifesting, so users should take care when setting and troubleshooting the ground protection functions, analyzing metering displays, and viewing oscillography files.

5.2. Energy-based Directional Discrimination

In order to cope with angle uncertainties during transient conditions and to provide for fast operation, the energy-based directional discrimination is applied. The principle reproduces to some extent electro-mechanical directional relays. One type of an electro-mechanical relay operates after a time required to move the relay “rotor” using the power:

$$P = S_1 \cdot S_2 \cdot \cos(\varphi) \quad (10)$$

where S_1 and S_2 are magnitudes of the polarizing and operate signals, respectively; and φ is an angle between them.

Thus, the contacts get closed if the energy was sufficient to complete movement of the relay "rotor". This approach gives an extra security because: (1) The mechanism moves faster if the signals are larger (2) The mechanism moves faster if the angle is closer to 0 degrees (3) The direction of the movement is positive (towards operation) if the fault is in the relay direction, and negative if the fault is in the reverse direction (owing to the cosine function).

These principles can be included in a microprocessor-based relay without any speed penalties.

In the proposed solution, the operate and polarizing signals are calculated accordingly to the required functionality. For example, for the forward-looking negative-sequence polarized negative-sequence IOC:

$$S_1 = I_2 \cdot 1 \angle RCA, \quad S_2 = -V_2 \quad (11)$$

where *RCA* is a Relay Characteristic Angle (setting).

The "operating energy" is calculated at each "protection pass", *n*, as a sum of the "operating power" over M_1 samples:

$$E_{op(n)} = \sum_{k=0}^{M_1-1} \left|S_{1(n-k)}\right| \cdot \left|S_{2(n-k)}\right| \cdot g\left(\Delta\varphi_{(n-k)}\right) \quad (12)$$

The function *g* is an equivalent of the cosine in the electro-mechanical world. The adopted shape of this function accommodates an adjustable limit angle and is shown in Fig.16.

The "restraining energy" uses the positive sequence current and is calculated as a maximum of the "restraining power" over M_2 samples:

- For a forward-looking element:

$$E_{rst(n)} = K_2 \cdot \left(MAX_{k=0}^{M_2-1}\left(\left|I_{1(n-k)}\right| \cdot \left|S_{2(n-k)}\right|\right)\right) \quad (13a)$$

- For a reverse-looking element:

$$E_{rst(n)} = -\frac{1}{4} K_2 \cdot \left(MAX_{k=0}^{M_2-1}\left(\left|I_{1(n-k)}\right| \cdot \left|S_{2(n-k)}\right|\right)\right) \quad (13b)$$

The constants M_1 and M_2 are internal relay parameters and in one relay they are fixed at a quarter, and a half of the power cycle, respectively.

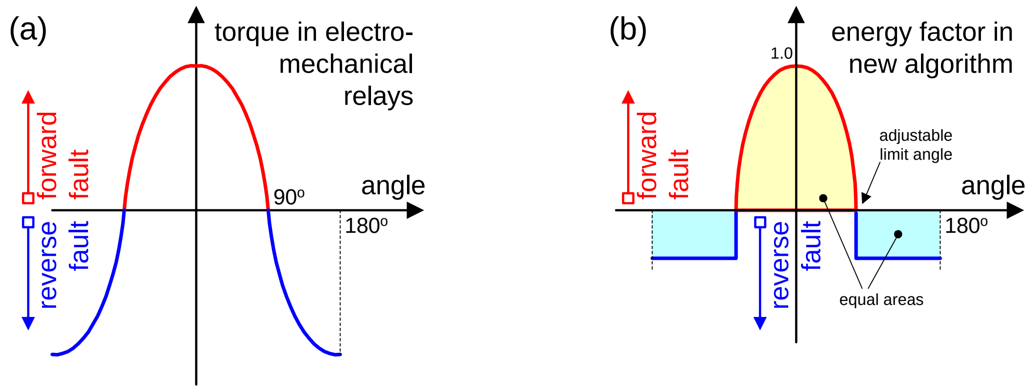

Figure 16. Electro-mechanical relays (a) vs. the new digital approach (b).

The K_2 constant is another internal relay parameter, which controls the balance between speed and security. The directional elements will tend to operate faster for lower values of K. One relay uses a K_2 of 0.25.

The forward-looking element operates if its operating energy is above its restraining energy; the reverse-looking element operates if its operating energy (negative) is below its restraining energy (negative).

As indicated by equations (13) the restraining energy is lower for the reverse-looking element. Because the element is meant to initiate the block rather than trip action, it is intentionally made faster and more sensitive.

5.3. Augmentation of the Polarizing Signal

As explained in Fig.17, the polarizing signal (negative- or zero-sequence voltage) could be low during forward faults, while it is not expected to be too low during reverse faults. This originates an idea of augmenting the polarizing signal by adding a small portion of the operating signal to ensure and speed-up operation.

This idea must be approached with caution because of the following factors:

(a) During high resistance reverse faults the polarizing signal could be quite low. The augmentation could override the correct “reverse” indication and cause maloperation if the overcurrent part is set too low.

(b) During transients such as three-phase symmetrical fault, the polarizing negative-

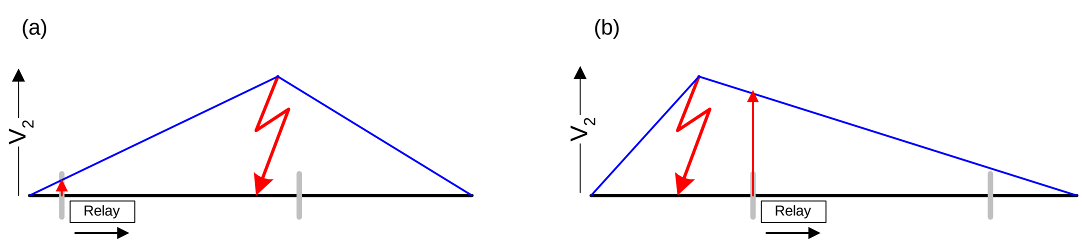

Figure 17. Polarizing voltage could be low during forward faults (a),
but is typically high for reverse faults (b).

sequence voltage could be low, while the current assumes spurious but significant values. The augmentation would bias the element to operate.

5.4. Current Reversals

During current reversals when a fault on a parallel line gets cleared and the pilot scheme will have to "reverse" its directional indications at both line ends simultaneously race conditions may potentially occur. The danger of race conditions results from the inertia associated with both power system signals and digital measuring algorithms of the relay.

The presented approach makes the reverse-looking elements faster than the forward-looking element helping to provide better coordination. It does not, however, solve the problem entirely and the current reversal issue must be addressed by the pilot schemes themselves (typically by extending the "reverse" indication for some time after it has been already present for some period of time).

6. Examples

Figs.18 and 19 illustrate the operation of the negative-sequence direction overcurrent element for a sample three-phase symmetrical fault (for the current waveforms see Fig.2, for the voltage waveforms see Fig.11). The overcurrent part is set very low and the element picks-up (Fig.19 – flags IOC FWD and IOC REV). The operating energy in the forward direction is well below the restraining energy (Fig.18, left) the forward-looking element does not maloperate (flags FWD and TRIP in Fig.19). The reverse-looking element establishes the block signal for a short period of time during the fault clearance.

Figs.20 and 21 illustrate the operation of a forward-looking negative-sequence IOC during a sample double-line to ground fault. The element operates in less than 10 msec.

7. Conclusions

The paper addresses the issues related to application of fast ground directional overcurrent protection functions.

The primary causes of spurious zero- and negative-sequence currents and voltages are discussed. Basic quantitative analysis of the level of the spurious signals is included.

A new solution for fast ground directional overcurrent function is presented. The solution combines the positive-sequence restraint with the energy-based directional discrimination.

The new solution allows for very sensitive settings without jeopardizing security or speed of operation.

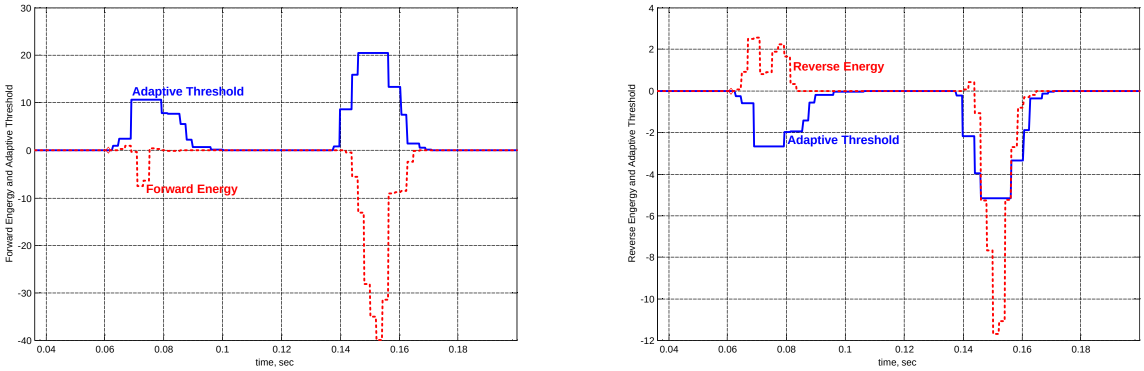

Figure 18. Sample three-phase symmetrical fault: Negative-Sequence Forward and Restraining (Adaptive Threshold) Energies (left); Negative-Sequence Reverse and Restraining Energies (right);

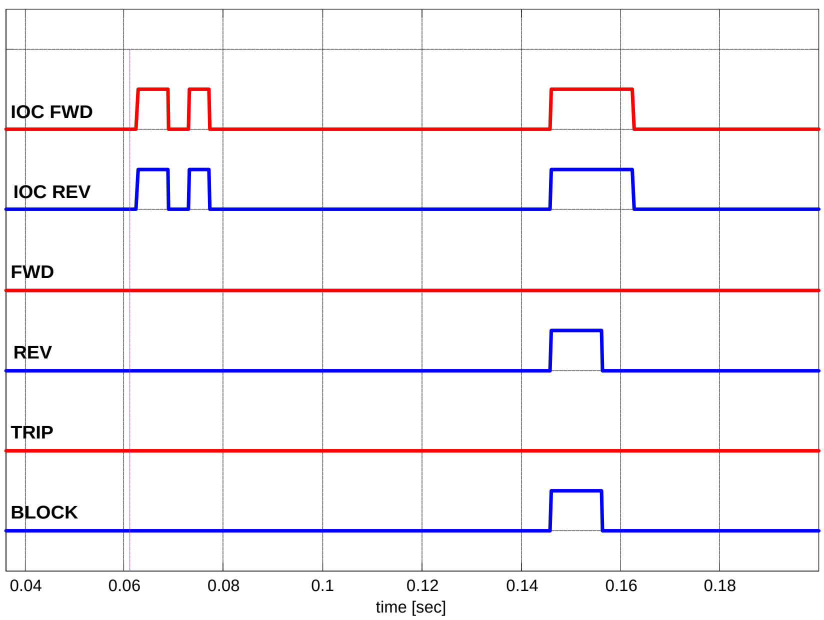

Figure 19. Sample three-phase symmetrical fault: Negative-Sequence Logic Flags. Neither forward nor reverse looking elements operates on fault inception. Short blocking pulse appears on fault clearing.

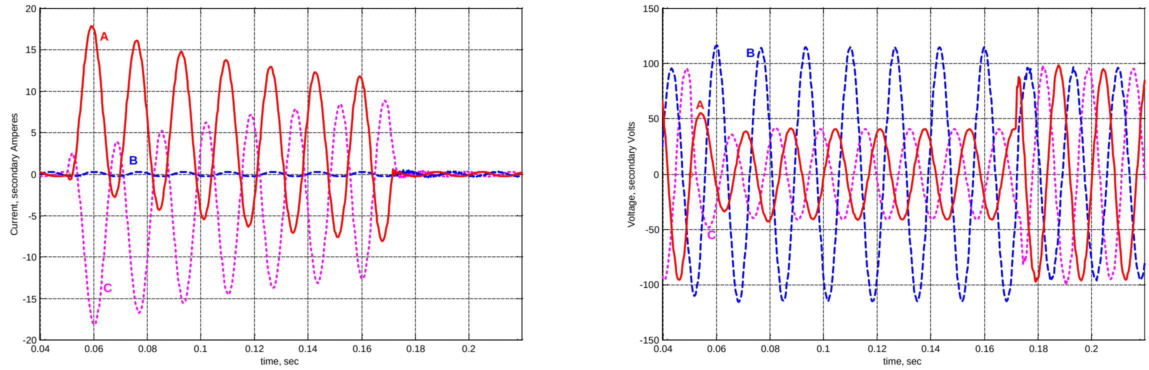

Figure 20. Sample forward double-line-to-ground fault: Current (left) and Voltage (right) Waveforms.

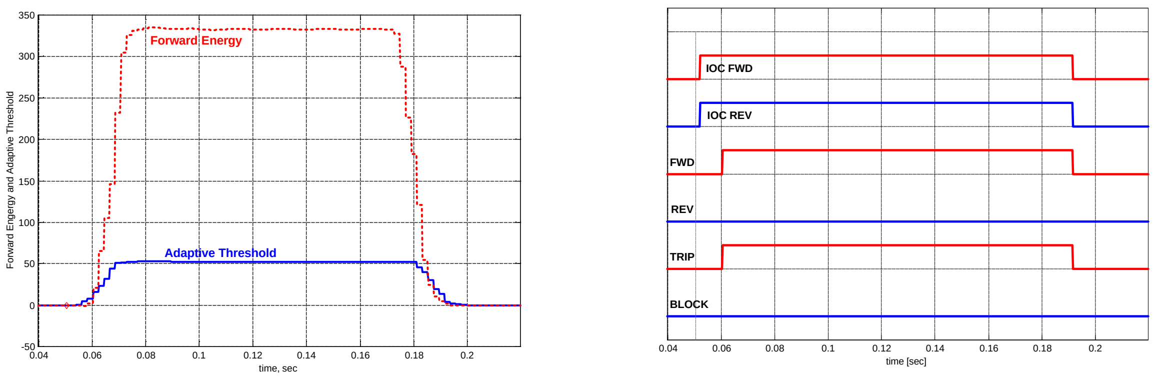

Figure 21. Sample double-line-to-ground fault: Negative-Sequence Forward and Restraining Energies (left); Negative-Sequence Logic Flags (right). The forward-looking element operates in 10 msec.

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Biographies

Bogdan Kasztenny received his M.Sc. (89) and Ph.D. (92) degrees (both with honors) from the Wroclaw University of Technology (WUT), Poland. Dr.Kasztenny worked as an Assistant Professor at WUT and as a Visiting Assistant Professor at Southern Illinois University (SIU) and Texas A&M University (TAMU). From 1994 till 1997 he was involved in applied research for Asea Brown Boveri. He spent one year as a Senior Fulbright Fellow at TAMU. Currently, Dr.Kasztenny works for GE Power Management as a Senior Application/Invention Engineer. Dr.Kasztenny is a Senior Member of IEEE, holds several patents, and has published more than 100 technical papers.

Dave Sharples after early experience with the Electricity Authority in the UK graduated from the University of Manchester (UK) with a M.Sc. (Tech) degree in 1963. After experience with the English Electric Meter Relay and Instrument Division he emigrated to Canada to join Ontario Hydro. Following early retirement in 1993 he has acted as a protection consultant, most recently with GE Power Management.

Bruce Campbell graduated in Electrical Technology from the Northern Alberta Institute of Technology in 1964. He has been involved in the design, commissioning and startup of high voltage electrical equipment in North America, the Caribbean, Africa, the Middle East and Southeast Asia. He is presently the chief application engineer for GE Power Management, involved in conceptual and scheme design for digital protective relays, and consulting on power system protection. He is a member of PES of the IEEE.

Marzio Pozzuoli graduated from Ryerson Polytechnical Institute, Toronto, Ontario Canada, in 1987 with a Bachelor of Electrical Engineering Technology specializing in control systems. He then worked for Johnson Controls designing industrial automation systems. He was involved in the design of Partial Discharge Analysis systems for large rotating electric machinery with FES International. In 1994 he joined General Electric – Power Management and is the Technology Manager responsible for the engineering and development of new products.