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PHASE SELECTION ALGORITHM IN SYMMETRICAL COMPONENTS CO-ORDINATES FOR DOUBLE-CIRCUIT SERIES COMPENSATED LINES

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Abstract. This paper deals with phase selection, which is one of the auxiliary algorithms for a line distance protection and fault location. The investigated phase selection algorithm has been formulated in symmetrical components co-ordinates. Overall flow chart of the phase selection process has been presented and discussed. Applying the simulation data, an application of the presented method to phase selection for a double-circuit series compensated line has been investigated. The phase selection results for a sample phase-to-phase-to-earth fault on such a transmission line have been presented and discussed. The thorough evaluation of the considered algorithm, performed with use of signals taken from ATP-EMTP versatile simulations of faults, has proved the validity of the phase selection algorithm and a possibility of its application to a double-circuit series compensated transmission line.

Keywords: double-circuit transmission line, series capacitor compensation, fault analysis, phase selection, digital signal processing, protective relay, fault locator

1. Introduction

Most of power-system faults occur in transmission networks, especially on overhead lines [1]. The highest fault rate of overhead lines is due to their inherent characteristic of being exposed to atmospheric conditions. Therefore, a number of researchers devoted great effort to developing digital algorithms for protective relay and fault locator devices. These devices are closely related, however, there are some important differences between them. Fault locators are used for pinpointing the fault position with possibly highest accuracy since this is required for the inspection-repair purpose. On the contrary, protective relays have to indicate the general area (defined by a protective zone) where a fault occurred [1].

Both the measurement and decision making of protective relays are performed in an on-line regime. In turn, high speed of operation of protective relays appears as a crucial requirement imposed on them. This is so because in order to prevent spreading out the fault effects the faulted line has to be switched off as quickly as possible. Conversely, the calculations of fault locators are performed in an off-line mode since the results of these calculations (position of the fault and in the case of some algorithms also the involved fault resistance) are for human users. This implies that the fault-location speed of calculations can be measured in seconds or even minutes [1].

Both protective relays and fault locators for performing their basic duty require identification of faults in terms of fault detection [2], directional discrimination [3] and phase selection [4]–[5]. This paper focuses on **phase selection** which determines faulted phases and also whether the earth is involved in an analysed fault or not. In other words, phase selection is aimed at fault type determination. Information on fault type is required by a distance line protection for composing a fault loop relevant for the analysed fault. In turn, one-end impedance-based fault location algorithms and some two-end algorithms require information on fault type as well [1].

Phase selection issue was studied in many references, however in great majority in relation to plain (uncompensated) power lines [4]–[5]. In this paper phase selection is considered as designated for application to a double-circuit transmission line with series capacitor compensation [6]–[7]. The studied phase selection method is formulated in symmetrical components co-ordinates and is based on checking the criteria angles of the symmetrical components signatures [4]–[5]. Just after a fault, these angles change significantly faster than magnitudes do.

2. Phase selection algorithm

The investigated phase selection method applies the following criteria [4]–[5]:

- angle of the ratio of a negative-sequence current and a positive-sequence current (1),
- angle of the ratio of a negative-sequence current and a zero-sequence current (2),
- significant increase of the positive-sequence current magnitude with absence of the negative- and zero-sequence components.

The first two criteria (1)–(2) are considered for all unsymmetrical faults while the third criterion only for three-phase balanced faults (Fig. 1). This is so since during three-phase balanced faults only positive-sequence component is present in current/voltage signals and as a result of that the criteria (1)–(2) become useless for such faults.

The criteria angles (1)–(2) are defined as follows:

$$\alpha = \text{angle}\left(\frac{\underline{I}_2}{\underline{I}_1}\right) \quad (1)$$

$$\beta = \text{angle}\left(\frac{\underline{I}_2}{\underline{I}_0}\right) \quad (2)$$

where:

$\underline{I}_1$, $\underline{I}_2$, $\underline{I}_0$ – phasors of positive-, negative- and zero-sequence current measured during a fault time interval lasting from the fault incipience instant up to the fault clearing instant.

In Fig. 1 the overall processing of three-phase input currents (i_a, i_b, i_c) for making the phase selection is presented.

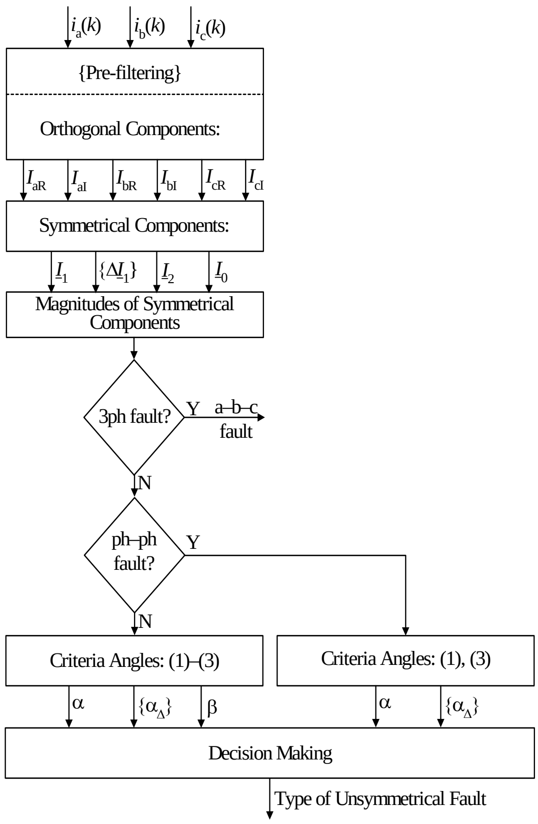


Fig. 1. Block diagram of signal processing for making phase selection

In order to emphasise the fault effect itself, i.e. to get the difference between the fault and pre-fault states, it is proposed to apply a superimposed positive-sequence current ($\Delta\underline{I}_1$) instead of a positive-sequence current ($\underline{I}_1$). As a result of that one obtains the criterion angle (3), which can be used as an alternative to the angle (1):

$$\alpha_\Delta = \text{angle}\left(\frac{\underline{I}_2}{\Delta\underline{I}_1}\right) \quad (3)$$

where: $\Delta\underline{I}_1 = \underline{I}_1 - \underline{I}_1^{\text{pre}}$ – superimposed positive-sequence current obtained by subtracting the pre-fault positive-sequence current ($\underline{I}_1^{\text{pre}}$) from this current taken from the fault time interval ($\underline{I}_1$).

Besides the compulsory calculations also certain optional elements (marked with the brackets {…}) are indicated in the flow chart of Fig. 1. In particular, the criterion angle (3) can be applied as an alternative to the angle (1). Also some pre-filtering can be optionally performed. Certainly, this introduces additional delay, but more stable results can be obtained due to implementation of the pre-filtering. For the off-line fault location application for which a speed of arriving at the decision is not critical as it is the case for high-speed protective relays use of the pre-filtering is certainly advantageous.

First, symmetrical components of the processed three-phase current are determined from the orthogonal components of the phase currents. Then, occurrence of a three-phase fault is identified. This is done by checking if an increase of the positive-sequence current magnitude is significant, i.e. exceeding a level of this magnitude during possible pre-fault load changes. At the same time the absence of the negative- and zero-sequence components has to be confirmed.

In the next step, the occurrence of phase-to-phase faults without involving the earth is identified. This can be done by checking the amplitude of the zero-sequence current, which is not present under such faults. Therefore, in such the cases (phase-to-phase faults without involving earth) the criterion angle β (2) is useless and thus the angle α (1) or alternatively α_Δ (3) can be applied for fault type determination.

Finally, a decision on fault type can be reached by considering the following criteria angles:

- α (1) or α_Δ (3) and β (2) – for phase-to-earth and phase-to-phase-to-earth faults
- α (1) or α_Δ (3) – for phase-to-phase faults.

Criteria angles at the steady state assume specific values – dependent on the fault type, as shown for the angle α_Δ (Fig. 2a) and β (Fig. 2b). These threshold values can be determined with use of the constraints (boundary conditions) for particular fault types and the fault current distribution factors [1]. When deriving for the angle α_Δ one takes that the fault current distribution factors for the positive- and negative-sequence have identical angles and there is no simplification here since this is basically the case for power transmission networks. In turn, some simplification, i.e. considering that the fault current distribution factors for the positive- and zero-sequence have identical angles, is taken for determining the angle β.

Strict determination of the angle α (not visualised in Fig. 2) is not possible due to presence of electro-motive forces in the positive-sequence network. However, it has been checked for the plain (uncompensated) transmission networks [4]–[5] that the threshold values determined for the criterion angle α_Δ (Fig. 2a) can be applied for the angle α as well, thus it is being assumed that $\alpha \cong \alpha_\Delta$. In the next section this will be checked for the case of a transmission network with series capacitor compensation.

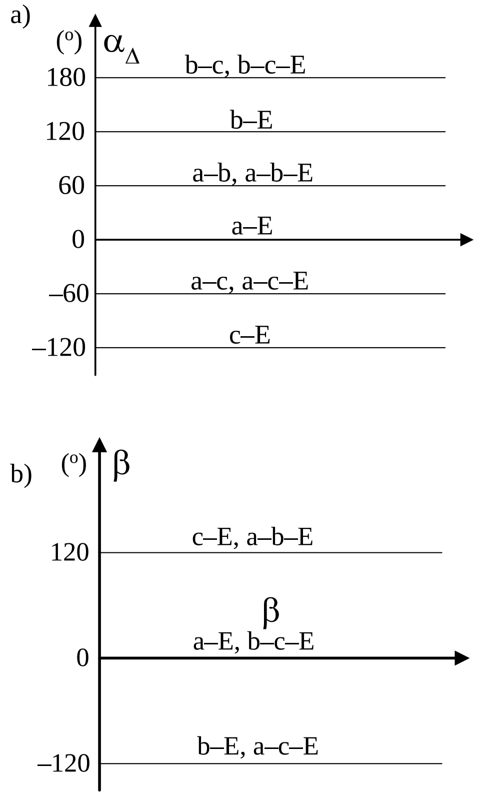


Fig. 2. Threshold values for: a) angle α_Δ (3), b) angle β (2)

From Fig. 2 one can conclude that the difference for the values of criteria angles for different fault types are quite high: 60° for the angle α_Δ (Fig. 2a) and 120° for the angle β (Fig. 2b). Therefore, the simplifying assumptions taken for determining the threshold values of the criteria angles appear as well justified. This allows us to apply comparatively wide margins around the determined threshold values (presented in Fig. 2), when making a decision on fault type. Basing on the study performed for the uncompensated lines [5], the following margins have been recommended for a practical application: the margin for the criterion angle α_Δ (or the angle α) set to $\pm 20^{\circ}$ and for the criterion angle β set to: $\pm 40^{\circ}$. Validity of this recommendation in relation to the series compensated lines is discussed in Section 3.

During faults there are some transients in the measured currents and thus the symmetrical components of the processed three-phase current are determined with certain errors. Moreover, accuracy and speed of operation are in opposition, so the developer should decide on some kind of compromise. Taking this decision the developer has to decide whether a particular design concerns the off-line fault location or on-line protection application. In the approach presented in this paper identical fast determination of symmetrical components of currents has been applied. However for fault location, additionally a half-cycle Fourier pre-filtration was introduced.

Let the phasor of the current from phase 'a' (similarly for the other phases) be defined as a complex number function:

$$\underline{I}_{\mathrm{a}}(k) = I_{\mathrm{aR}}(k) + \mathrm{j}\, I_{\mathrm{aI}}(k) \qquad (4)$$

where k denotes a sample number.

The orthogonal components involved in (4) may be obtained from two consecutive samples of the processed current [1]:

$$I_{\mathrm{aR}}(k) = \frac{i_{\mathrm{a}}(k) + i_{\mathrm{a}}(k-1)}{2\cos(\omega_1 T_{\mathrm{s}}/2)} \qquad (5)$$

$$I_{\mathrm{aI}}(k) = \frac{-i_{\mathrm{a}}(k) + i_{\mathrm{a}}(k-1)}{2\sin(\omega_1 T_{\mathrm{s}}/2)} \qquad (6)$$

where: $i_{\mathrm{a}}(k)$, $i_{\mathrm{a}}(k-1)$ are k-th and $(k-1)$-th samples of the input current (here from the phase 'a'); ω_1 – angular frequency of the fundamental component, T_{s} – sampling period.

Now, having the phasor's estimates for the three-phase current (for the phase 'a' presented in (5)–(6) and analogously for the remaining phases) it is possible to determine the symmetrical components of the current. For this purpose the following way of determining the orthogonal components of symmetrical components phasors [1] has been chosen:

$$\text{zero-sequence:} \begin{cases} I_{0\mathrm{R}} = \left(I_{\mathrm{aR}} + I_{\mathrm{bR}} + I_{\mathrm{cR}}\right)/3 \\ I_{0\mathrm{I}} = \left(I_{\mathrm{aI}} + I_{\mathrm{bI}} + I_{\mathrm{cI}}\right)/3 \end{cases} \qquad (7)$$

positive-sequence: (8)

$$\begin{cases} I_{1\mathrm{R}} = \left(I_{\mathrm{aR}} - \frac{1}{2}I_{\mathrm{bR}} - \frac{\sqrt{3}}{2}I_{\mathrm{bI}} - \frac{1}{2}I_{\mathrm{cR}} + \frac{\sqrt{3}}{2}I_{\mathrm{cI}}\right)\Big/3 \\ I_{1\mathrm{I}} = \left(I_{\mathrm{aI}} - \frac{1}{2}I_{\mathrm{bI}} + \frac{\sqrt{3}}{2}I_{\mathrm{bR}} - \frac{1}{2}I_{\mathrm{cI}} - \frac{\sqrt{3}}{2}I_{\mathrm{cR}}\right)\Big/3 \end{cases}$$

negative-sequence:

$$\begin{cases} I_{2R} = \left(I_{aR} - \frac{1}{2} I_{bR} + \frac{\sqrt{3}}{2} I_{bI} - \frac{1}{2} I_{cR} - \frac{\sqrt{3}}{2} I_{cI} \right) \Big/ 3 \\ I_{2I} = \left(I_{aI} - \frac{1}{2} I_{bI} - \frac{\sqrt{3}}{2} I_{bR} - \frac{1}{2} I_{cI} + \frac{\sqrt{3}}{2} I_{cR} \right) \Big/ 3 \end{cases} \quad (9)$$

where the 1st subscript (0, 1, 2) denotes the zero-, positive- or negative-sequence while the 2nd subscript (R, I) is used for marking the real/imaginary part of the phasor, respectively.

3. Atp-emtp based evaluation

Performance of the presented method was analysed using a digital model running on ATP-EMTP [8] simulation software program. A double-circuit transmission series-compensated line was used in the simulation. Series capacitors with adequate Metal-Oxide Varistors (MOVs) were placed in both parallel lines: AA-BA and AB-BB (Fig. 3).

The main parameters of the considered system are as follows:

- rated voltage: 400kV, system frequency: 50 Hz
- phase angle of EMFs: System A→0°, System B→–30°
- positive- and zero-sequence impedance of systems: $\underline{Z}_{1\Sigma A}=\underline{Z}_{1\Sigma B}=(1.307+\varphi 15)\Omega$, $\underline{Z}_{0\Sigma A}=\underline{Z}_{0\Sigma B}=(2.318+\varphi 26.5)\Omega$
- line length: 300km
- Line impedances for positive-, zero- and mutual zero-sequence: $\underline{Z}_{1L}=(0.0267+j0.3151)\Omega$/km, $\underline{Z}_{0L}=(0.275+j1.026)\Omega$/km, $\underline{Z}_{0m}=(0.198+j0.628)\Omega$/km
- Line shunt capacitances for positive-, zero- and mutual zero-sequence: $C_{1L}=0.013\mu$F/km, $C_{0L}=0.0085\mu$F/km, $C_{0m}=0.005\mu$F/km
- series compensation degree: 70% (in both parallel lines), position of capacitors: 0.5 p.u. (in the middle)
- MOV characteristic: $i_{MOV} = P(v_{MOV}/V_{REF})^q$, where: P=1kA, V_{REF}=150kV, q=23.

The developed ATP-EMTP model includes the Capacitive Voltage Transformers (CVTs) and the Current Transformers (CTs). The analogue filters with 350Hz cut-off frequency have been also included. The sampling frequency of 1000 Hz has been used.

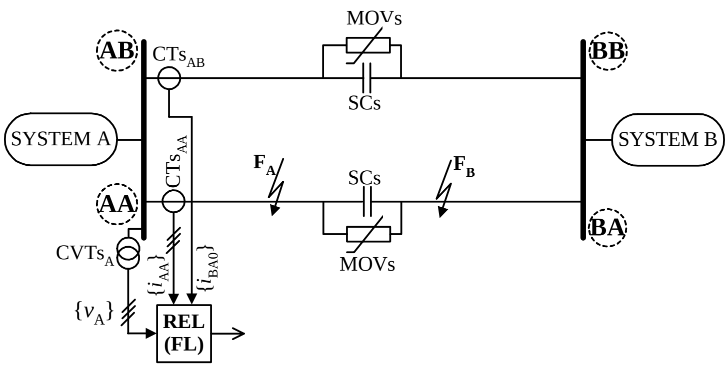
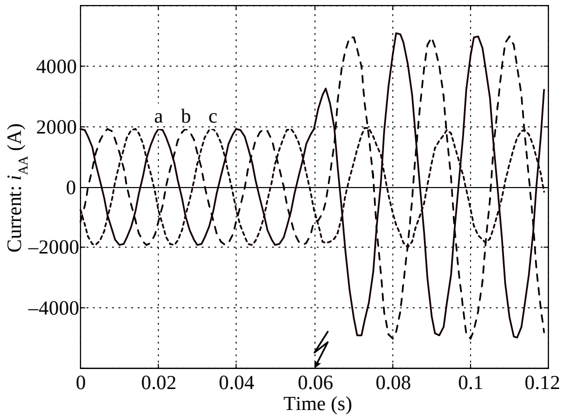


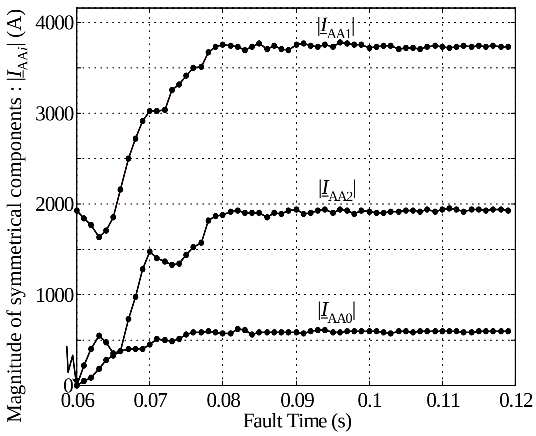
Fig. 3. Scheme of transmission system with double-circuit series compensated line for analysis of phase selection for relay (REL) or fault locator (FL)

Different scenarios with changing of a fault place (faults in front of SCs&MOVs: F_A and behind them: F_B) have been considered in the performed evaluation study. Also fault type, fault resistance and equivalent system impedances have been changed. The obtained results of the test cases are all correct in the determination of the fault-type.

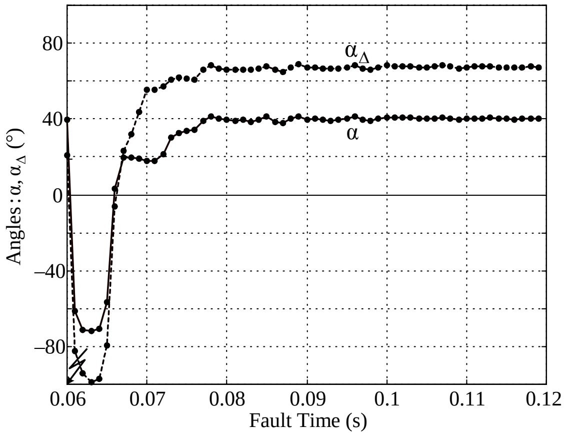
Phase selection results for the example fault are presented in Fig. 4. The specification of the fault applied on the line AA-BA: a–b–g fault; distance to fault from the bus AA: 0.6 p.u. (thus fault F_B, i.e. behind SCs&MOVs as seen from the relaying point AA); fault resistance: 10Ω. The processed three-phase current from the faulted line (i_{AA}) is shown in Fig. 4a. Since this is a fault behind SCs&MOVs, d.c. components are not contained in the currents from faulted phases (a, b). However, some sub-harmonics present in the currents cause the fluctuations in the magnitudes of the symmetrical components (Fig. 4b). Since all symmetrical components (positive-, negative- and zero-sequence) are present, a hypothesis that this is a three-phase fault or phase-to-phase fault is not valid. As a result of that, the phase selection narrows to deciding whether it is phase-to-earth or phase-to-phase-to-earth fault. The criteria angles shown in Fig. 4c and d clearly indicate that this is a–b–g fault. The threshold value of the criteria angle α_Δ for a–b–g fault equals 60° (Fig. 2a – the case of uncompensated line). However, for the considered fault (Fig. 4c) this angle differs from the threshold value by around +10°, thus it is still within the realistic margin $\pm 20^o$ around the determined threshold value. In turn, the criteria angle α differs from the threshold value by around (–20°), thus at the border of the realistic margin. Also the other studied fault cases have shown that in case of a series compensated line it is advisable to use the criterion angle α_Δ and not the angle α. In turn, the criterion angle β (Fig. 4d) enters reliably the region of the vicinity of threshold value of 120° with the margin set to $\pm 20^{\circ}$ very fast (below half a fundamental frequency cycle).



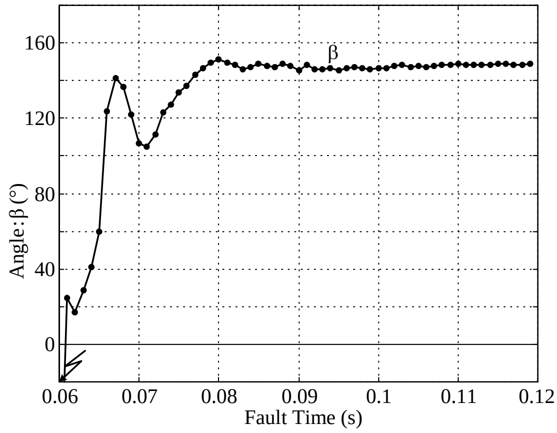
a)



b)



c)



d)

Fig. 4. Phase selection example:
a) three-phase current,
b) magnitudes of symmetrical components of currents,
c) criteria angles: α, α_Δ,
d) criterion angle β

4. Conclusions

This paper shows that information contained in symmetrical components of measured currents can be effectively utilised for making phase selection for a double-circuit transmission line with series capacitor compensation. Digital processing of three-phase current from the faulted line has been considered for both a line distance protection and a fault locator applications, differing only in introducing an extra pre-filtering in the case of a fault locator.

The carried out evaluation with use of the fault data obtained from versatile simulation of faults on the test transmission network with a double-circuit series compensated transmission line has proved that the studied phase selection algorithm can be effectively applied to such a specific network as well. The included example illustrates good performance of the investigated phase selection technique.

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АЛГОРИТМ ВИБОРУ ФАЗИ У КООРДИНАТАХ СИМЕТРИЧНИХ СКЛАДОВИХ ДЛЯ ДВОКОНТУРНИХ ПОСЛІДОВНО-КОМПЕНСОВАНИХ ЛІНІЙ

Є. Росоловскі, Я. Іжуковскі

Ця стаття присвячена питанню вибору фази, що є одним з додаткових алгоритмів для віддаленого захисту ліній та визначення місця пошкодження. Досліджуваний алгоритм вибору фази сформульовано в координатах симетричних складових. Представлено й розглянуто загальну схему процесу вибору фази. Досліджено застосування запропонованого методу до вибору фази для двоконтурної послідовно-компенсованої лінії з використанням тестових даних. Показано й проаналізовано результати вибору фази для прикладу двофазного замикання на землю на такій лінії пересилання. Скрупульозна оцінка запропонованого алгоритму, проведена з використанням сигналів, отриманих на підставі ATP-EMTP різнобічного моделювання аварійних режимів, доказала дієвість запропонованого алгоритму вибору та можливість його застосування до двоконтупних послідовно компенсованих ліній електро-пересилання.

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