A Novel Fault Classification Technique for High Speed Protective Relaying of Transmission Lines

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Abstract—**This paper presents a new algorithm for faulty phase selection in transmission lines. The algorithm is based on a limited soft processing of the 3-phase and the zero-component current phasors. Current phasors are determined by using a pair of short length data window filters giving orthogonal outputs – phasor components. The soft processing means here that, generally, the operations like min and max are used rather than multiplication or summation of two or more arguments.**

Keywords- line protection; fault classification; decision making; fault type; soft computing

I. INTRODUCTION

The type of fault determination algorithms are usually categorized as auxiliary functions used in line protection relays for composing adequate faulty loops. In modern solutions, especially in the fast relays, a type of fault indicator may be applied as the one of the criterion values as well. In such a case the responsibility of this function increases and the result should be determined reliably and close to the fault inception detection as much as possible. Fast and reliable fault type determination of the fault in electric power lines is of great importance both for power companies dealing with electric energy distribution and for end users of electric energy. Quick and exact fault type selection affects the quality of power system protection. A means for fault phase selection and fault type determination is usually a part of a digital protection relay located in power stations or substations. Depending on the fault type, different current and voltage fault loops are distinguished and processed in the protection relay. Therefore the proper fault type selection influences the final operation of the protection relay and an error in the fault type identification may lead to mal-operation of the protection relay.

A protection relay may be basically considered as a classifier device (Fig. 1). In such a solution the fault-type discriminator is an essential part of the protection algorithm and plays the very important role in the final decision-making. It is also very important part of another automatic devices, as for example, a fault locator embedded into relay or also as autonomous device connected to Digital Fault Recorder [13].

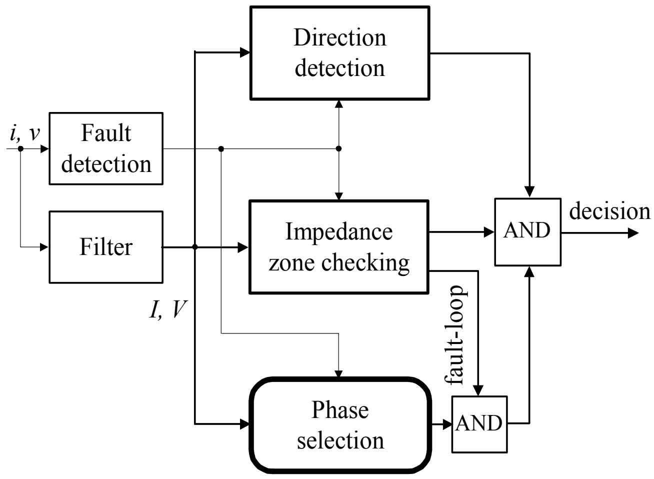

Figure 1. Relay as a classifying device

Generally, changing of different electrical values during fault are utilized for type of fault determination [2, 7]. The simplest method assumes that a phase impedance (resulting from a phase voltage and current) for a phase involved in a fault is below a certain level – correlated with the maximum load. In addition, the zero-sequence quantities (current and/or voltage) are used as indicators of faults with the ground. Instead of processing voltage and current samples directly, superimposed current and voltage samples can be used for fault classification too [12, 13].

Another family of methods uses relationships between the symmetrical components of the fault current and/or voltage. For speeding up of detection and to obtain more reliable decision, information about phase angle is used [7]. Two fault signatures: negative-sequence vs. positive-sequence and negative-sequence vs. zero-sequence current and/or voltage are used simultaneously. The criterion is based on checking the relations between adequate post-fault angles, which change significantly faster just after fault than do magnitudes. Generally, the approach based on using symmetrical components introduces the following three criteria spaces [7]:

- negative-sequence vs. positive-sequence relation;
- negative-sequence vs. zero-sequence relation; and
- significant increase of the positive-sequence quantity with absence of the negative- and zero-sequence components.

Using these criteria spaces it is possible to identify different types of fault. Detailed criteria can be defined with respect to different features of the considered sequence components. The second condition was added because it is well known that the presence of large negative-sequence components in the relay input signals reveals the occurrence of a fault in the supervised system. This is so for all faults but excluding the case of the balanced three-phase fault, for which only the positive-sequence current is present, however, with the increased value after a fault occurrence. Unfortunately, during faults there are transients in the measured currents and thus the symmetrical components are determined with certain errors. Moreover, accuracy and speed of operation are in opposition, so the developer should decide on some kind of compromise. Symmetrical components are defined for phasors of a three-phase system. In fast procedures the current phasors should be calculated with use of an adequately simple method with relatively short delay. Such a method based on classical Fourier algorithm is presented below.

Aforementioned orthogonal components are sinusoidal in the steady state. Unfortunately, during faults the currents contain high-frequency noise and thus the phasor estimates are considerably deformed, which should be taken into considerations in the further steps of the algorithm. Each type of fault is characterized by the appearance of the specific set of symmetrical component (or components) of currents [7, 13]. An abnormal situation is identified if the adequate symmetrical component exceeds the pre-defined threshold. It is important that this threshold setting should be relatively high in order to avoid false operation during changes in normal load conditions of the system. The transient measuring errors, which have sufficient influence on the final result, especially when a fast decision is expected, may be handled by using of different, so called, 'soft processing' methods, which includes application of:

- fuzzy logic based methods [5, 7];
- ANN with different structures [1, 4, 8, 9, 14];
- wavelet transformation [3, 10, 17];
- pattern recognition [6];
- probabilistic approach [11];
- combination of the above with some other approaches [3, 15, 16].

Application of one of the mentioned solution may improve the faulted phase selection algorithm, however this usually entails complication of the algorithm and introduces an adequate output delay.

In the proposed algorithm the criteria values are defined in a traditional form as relations between the respective pre- and post-fault current magnitudes [12, 18]. These relations define suitable logic variables which leave directly to final decision. A novel solution in this traditional approach consists in utilizing a simple soft processing in the way of calculation of the mentioned relations.

The presented method may be applied for faulted phase selection and fault type determination in both series compensated and uncompensated power lines, fit for use in the power industry for overhead and overhead-cable transmission or distribution lines. It has been evaluated using elaborate modeling and simulation set up that represents a segment of 400 kV transmission network with parallel series-compensated line.

II. Proposed Algorithm

In the traditional algorithm the phase selection algorithm is common for both single-phase-to-ground and multi-phase faults [13]. The phase selection is performed by comparison of changes in the phase-to-phase currents between phases A and B, B and C, and C and A. The changes in the phase-to-phase currents are obtained by subtracting the actual fault currents with corresponding pre-fault quantities. The quantities (changes of currents) should be above certain operation levels in order to indicate the faulted phase. Input currents can be measured with application of short-window Fourier algorithm or some other methods [13].

A. Orthogonal components determination

Let the current phasor be represented in the form:

$$\underline{I}_{(k)} = I_{\mathrm{x}(k)} + \mathrm{j}I_{\mathrm{y}(k)} \tag{1}$$

where k indicates a sample number.

For the considered procedures, the current phasors can be calculated in shorter than one period data window. Generally, the phasor components are calculated as follows [13]:

$$\begin{aligned} I_{\mathrm{x}(k)} &= p_{\mathrm{x}} \sum_{j=0}^{k_{\mathrm{M}}-1} h_{\mathrm{x}(j)} i_{(k-j)} \\ I_{\mathrm{y}(k)} &= p_{\mathrm{y}} \sum_{j=0}^{k_{\mathrm{M}}-1} h_{\mathrm{y}(j)} i_{(k-j)} \end{aligned} \tag{2}$$

where:

k_{M} – number of samples in data window (filter length),

$h_{\mathrm{x}(l)} = \cos(a_0 + (l-1)a)$,

$h_{\mathrm{y}(l)} = \sin(a_0 + (l-1)a)$,

$h_{\mathrm{x}(k_{\mathrm{M}}-l+1)} = h_{\mathrm{x}(l)}$, $h_{\mathrm{y}(k_{\mathrm{M}}-l+1)} = -h_{\mathrm{y}(l)}$, for l=1, 2, …, k_1,

$a = \frac{2\pi}{N}$, N – number of samples per cycle,

$k_1 = \frac{k_{\mathrm{M}}-1}{2}$, $a_0 = -k_1 a$, $h_{\mathrm{x}(k_1+1)} = 1$, $h_{\mathrm{y}(k_1+1)} = 0$ – for odd k_{M},

$k_1 = \frac{k_M}{2}$, $a_0 = -k_1 a + \frac{a}{2}$ – for even k_M.

Coefficients p_x and p_y are calculated from the relation:

$$\begin{bmatrix} p_x & p_{xy} \\ p_{xy} & p_y \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} \sum_{j=0}^{k_M-1} h_{x(j)}^2 & \sum_{j=0}^{k_M-1} h_{x(j)} h_{y(j)} \\ \sum_{j=0}^{k_M-1} h_{x(j)} h_{y(j)} & \sum_{j=0}^{k_M-1} h_{y(j)}^2 \end{bmatrix}^{-1} \quad (3)$$

In general case, the coefficients $p_x = p_y$ vary in time and they are constant when data window length is multiple of a half period, e.g. for $k_M = N$ (full period), $p_x = p_y = \sqrt{2}/N$.

B. Derivation of the algorithm

In the considered algorithm the faulty phases are determined on the basis of the following current quantities:

- difference of the phase currents (phasors):

$$\begin{aligned} \underline{I}_{AB} &= \underline{I}_A - \underline{I}_B \\ \underline{I}_{BC} &= \underline{I}_B - \underline{I}_C \\ \underline{I}_{CA} &= \underline{I}_C - \underline{I}_A \end{aligned} \quad (4)$$

- neutral current:

$$\underline{I}_N = \underline{I}_A + \underline{I}_B + \underline{I}_C \quad (5)$$

- difference of the pre-fault phase currents (phasors):

$$\begin{aligned} \underline{I}_{AB}^{pre} &= \underline{I}_A^{pre} - \underline{I}_B^{pre} \\ \underline{I}_{BC}^{pre} &= \underline{I}_B^{pre} - \underline{I}_C^{pre} \\ \underline{I}_{CA}^{pre} &= \underline{I}_C^{pre} - \underline{I}_A^{pre} \end{aligned} \quad (6)$$

In the traditional approach the selector is current delta based and, therefore, the following incremental currents are calculated:

$$\begin{aligned} \Delta I_{AB} &= \mathrm{abs}\left(\underline{I}_{AB} - \underline{I}_{AB}^{pre}\right) \\ \Delta I_{BC} &= \mathrm{abs}\left(\underline{I}_{BC} - \underline{I}_{BC}^{pre}\right) \\ \Delta I_{CA} &= \mathrm{abs}\left(\underline{I}_{CA} - \underline{I}_{CA}^{pre}\right) \end{aligned} \quad (7)$$

For scaling the above currents, the maximum incremental current is calculated:

$$\Delta I_{mx} = \max\left(\Delta I_{AB}, \Delta I_{BC}, \Delta I_{CA}\right) \quad (8)$$

The phase-to-ground fault is determined on the basis of the following current:

$$I_{SG} = \mathrm{abs}\left(\underline{I}_N\right) / c_{F0} - \min\left(I_{rated}, \Delta I_m\right) \quad (9)$$

where I_{rated} is the line rated current (rms).

The phase-to-phase fault loop selection is assured by the following auxiliary indices:

$$\begin{aligned} I_{SA} &= \min\left(\Delta I_{AB}/c_{F1} - \Delta I_{mx}, \Delta I_{CA}/c_{F1} - \Delta I_{mx}, \Delta I_{mx} - \Delta I_{BC}\right) \\ I_{SB} &= \min\left(\Delta I_{BC}/c_{F1} - \Delta I_{mx}, \Delta I_{AB}/c_{F1} - \Delta I_{mx}, \Delta I_{mx} - \Delta I_{CA}\right) \\ I_{SC} &= \min\left(\Delta I_{CA}/c_{F1} - \Delta I_{mx}, \Delta I_{BC}/c_{F1} - \Delta I_{mx}, \Delta I_{mx} - \Delta I_{AB}\right) \end{aligned} \quad (10)$$

$$\begin{aligned} I_{\Delta A} &= \min\left(\Delta I_{AB}, \Delta I_{CA}\right) - I_{SA} \\ I_{\Delta B} &= \min\left(\Delta I_{BC}, \Delta I_{AB}\right) - I_{SB} \\ I_{\Delta C} &= \min\left(\Delta I_{CA}, \Delta I_{BC}\right) - I_{SC} \end{aligned} \quad (11)$$

The setting coefficients c_{F0}, c_{F1} in (9) and (10) are chosen for determination of adequate thresholds, which subdivide a whole space created by the fault indicators.

Adequate combination of the above current indices leads to the final selection indicators:

- phase-to-ground faults:

$$\begin{aligned} F_1 &= \left(\min\left(I_{SA}, I_{SG}\right) + \min\left(I_{\Delta B}, I_{\Delta C}\right) - I_{\Delta A}\right) / \Delta I_{mx} \text{ – A-G} \\ F_2 &= \left(\min\left(I_{SB}, I_{SG}\right) + \min\left(I_{\Delta C}, I_{\Delta A}\right) - I_{\Delta B}\right) / \Delta I_{mx} \text{ – B-G} \\ F_3 &= \left(\min\left(I_{SC}, I_{SG}\right) + \min\left(I_{\Delta A}, I_{\Delta B}\right) - I_{\Delta C}\right) / \Delta I_{mx} \text{ – C-G} \end{aligned} \quad (12)$$

- phase-to-phase faults:

$$\begin{aligned} F_4 &= \min\left(I_{SA}, I_{SB}\right) / \Delta I_{mx} \text{ – A-B} \\ F_5 &= \min\left(I_{SB}, I_{SC}\right) / \Delta I_{mx} \text{ – B-C} \\ F_6 &= \min\left(I_{SC}, I_{SA}\right) / \Delta I_{mx} \text{ – C-A} \end{aligned} \quad (13)$$

- phase-to-phase-to-ground faults:

$$\begin{aligned} F_7 &= F_1 + F_2 + F_4 \text{ – A-B-G} \\ F_8 &= F_2 + F_3 + F_5 \text{ – B-C-G} \\ F_9 &= F_3 + F_1 + F_6 \text{ – C-A-G} \end{aligned} \quad (14)$$

- three-phase fault:

$$F_{10} = \min\left(I_{\Delta A}, I_{\Delta B}, I_{\Delta C}\right) / \Delta I_{mx} \quad (15)$$

The above indices form the following vector:

$$\mathbf{F} = \left\{F_{flt}\right\} = \left[F_1 \ \ .. \ \ F_{10}\right] \quad (16)$$

When a fault is detected the indicator with maximum value points to the selected type of fault. That can be described as:

$$F_{FS} = \max_{i=1..10}(\{F_i\}) \quad (17)$$

The fault selection index (FS) indicates a number of indicator from that determined from (12)–(16) which directly points on the type of fault.

The auxiliary indices calculated in (9)–(11) determine the percentage of the largest faulted value, and then subtracts it from the phases/neutral currents. That calculations are provided on the basis of min/max operations what assures satisfactory flexibility of the algorithm to eventual ambiguity of the final decision. The proposed procedure also gives a reliable estimate for 3-phase fault. In such the case, when fault-loops are to be indicated, one of the faulted phases does not reach adequate level, and the phase remains undetected. That inconvenience is removed here because the operation (15) have a good selection property.

C. *Algorithm description*

The proposed algorithm is realized in the following steps:

1. The 3-phase currents are pre-filtered by using of the Fourier filter with data length of N/4 samples (quarter of period). Results in the form of phasors orthogonal components for three phase currents are placed in memory buffer length on 2N records (this length can be adequately adjusted). This buffer memorizes the pre-fault values which are used in the algorithm. The pre-fault values are taken from the buffer with adequate delays.

2. The fault type is estimated according to the presented algorithm. Its distinguished feature consists in using of 'soft' operators like: min(), max() instead of crisp logical operators (greater than, less than). The decision is determined for the consecutive steps (samples) by calculating prescribed auxiliary indices – as is explained in the algorithm description. The calculation is initiating by the fault inception marker, with using of pre- and post- fault measured values.

Because of unstable results just after the fault inception detection, results for the first two samples – counting from the algorithm starting - are removed.

3. In the first stage, the auxiliary indices are calculated: equations (4)–(8). Indices calculated in (1)–(3) are based on incremental pre- post fault current values. Indices calculated in (10) and (11) are used for indication the phases involved in the fault while (9) indicates if there is a phase-to-ground fault. All these indices are continues real values – not logical.

4. Based on these indices in the procedure determined by (12)–(15) the real-valued indicators are calculated. These indicators are divided into four groups: (12) – for indication of phase-to-ground faults, (13) – with respect to phase-to-phase faults, (14) – for phase-to-phase-to-ground faults, and (15) – for 3-phase fault. The calculated quantities are so scaled (in the first stage) that the greatest indicator points to the type of fault.

The procedure (16) can be used for ordering the calculated indicators and coding them with numbers 1–10. The indicator with the greatest value points on the selected type of fault.

III. MODEL IMPLEMENTATION AND SIMULATION RESULTS

The performance of the presented method was analyzed using a software model running on ATP-EMTP [19] simulation program. A double-circuit transmission series-compensated line is used in the simulation. A series capacitors with adequate MOV scheme were placed at both ends of lines (Fig. 2).

The main parameters of the considered system are:

- rated voltage: 400kV, system frequency: $f_N = 50$ Hz;
- basic system impedance (Z_S):
  $Z_{S0} = (1.167 + j11.25)\ \Omega$, $Z_{S1} = (0.656 + j7.5)\ \Omega$,
  in the considered example: $Z_{SA} = 2\ Z_S$, $Z_{SB} = 4\ Z_S$;
- line parameters:
  line length: 300km,
  $Z_1 = (0.0267 + j0.3151)\ \Omega$/km,
  $C_1 = 0.013\ \mu$F/km,
  $Z_0 = (0.275 + j1.026)\ \Omega$/km
  $C_0 = 0.0085\ \mu$F/km,
  $Z_{0m} = (0.200 + j0.628)\ \Omega$/km;
- series capacitors location: 4 SCs each at the line ends;
- series compensation degree: 70% ($2\times X_c = 2\times 66.2\ \Omega$) at both lines.

Different scenarios with changing of a fault place and type (including cross-phase fault between two parallel lines), fault resistance and equivalent system impedances were performed for evaluation of the method. The obtained results of the test cases were all correct in the estimation of the fault-type.

For illustration, in the following example it is considered A-B-G fault in Line #1 at the distance $l = 0.7$ line length seen from bus A (Fig. 2). Three-phase current and voltage waveforms recorded at bus A are depicted in Fig. 3. Fault resistance R_F=20 Ω and time inception t_F=0.06s.

Change of the fault-type indicators just after fault is presented in Fig. 4. For better tracking of the results the time axis is counting in sample number starting from the fault detection point. Outputs for first two samples are omitted for elimination of the extensive transients at the beginning of the procedure. It can be seen that the curve standing for F7 (A-B-G fault) fast takes the maximum value.

It is evident for this case that a division of a criteria space is sufficiently clear and the selection of the greatest value from a set of ten indicators can be made with no doubt. That is illustrated in Fig. 5 which presents a waveform related to the final decision.

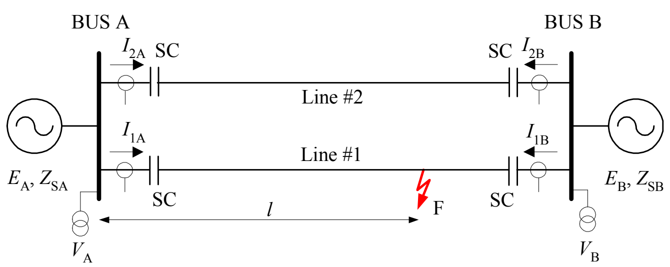

Figure 2. Scheme of the analyzed system.

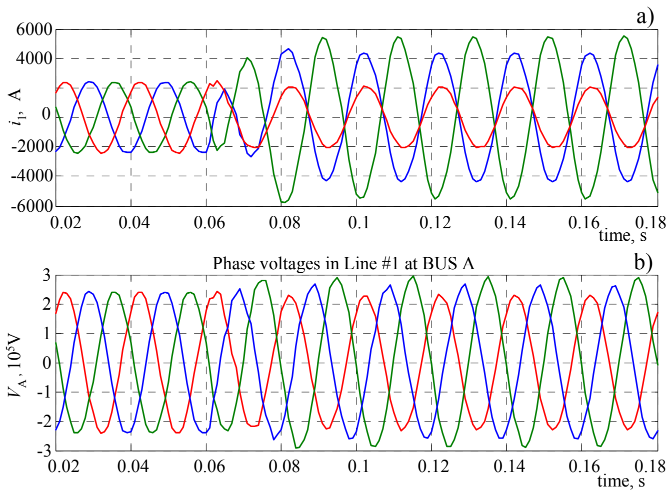

Figure 3. Currents (a) and voltage (b) waveforms during A-B-G fault in Line #1

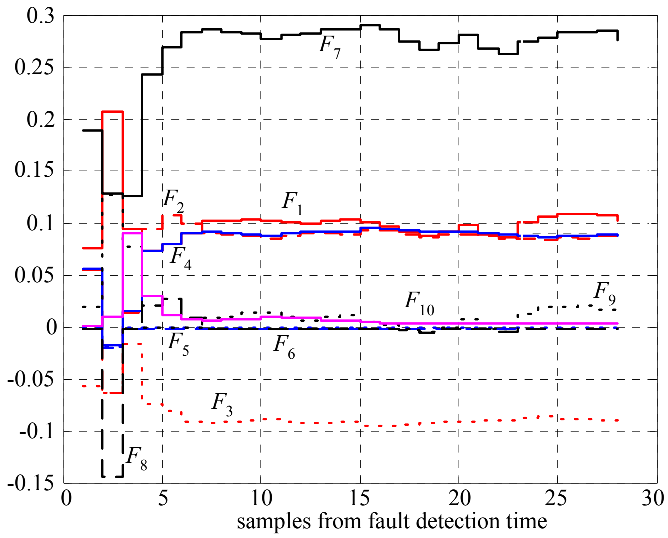

Figure 4. Change of the fault-type indicators

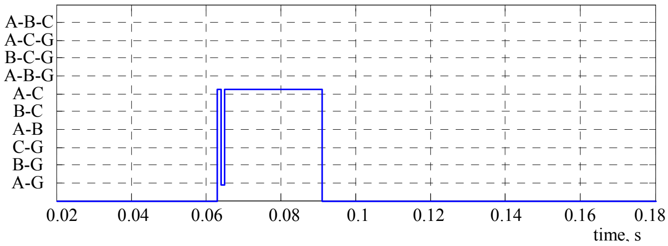

Figure 5. Resulting indicator for type of fault selection

It can be seen in Fig. 5 that in the transient period just after fault the algorithm changes decision: A-B-G, A-B and then switches to correct stable result for A-B-G fault. However, even in the transient period the decision is not false.

IV. Conclusions

Fast and reliable fault type determination of the fault in electric power lines is of great importance both for power companies dealing with electric energy distribution and for end users of electric energy. Quick and exact fault type selection affects the quality of power system protection. Such an information is also important for correct performance of other automation devices, as for example, fault locators. Any fault detection and classification technique should be capable of giving satisfactory performance under a wide variety of system and fault conditions.

This paper presents a novel technique for determining the faulty phases in a transmission system. The suggested algorithm is based on measurement of phase currents and fast estimation of phasor components in relatively short data window. The main selection procedure utilizes relations between current magnitudes for different possible fault loops. It also uses the relative magnitudes of the neutral and phase currents to differentiate between grounded and ungrounded faults. The proposed technique is independent of the system configuration, and the power system operating conditions during faults. The technique is also computationally efficient. The simple technique does not require the programming of any system dependent parameters, such as zero-sequence impedances, thereby providing more flexibility to users.

To ascertain the effectiveness of the technique, it was tested with ATP-EMTP simulated data. Obtained results show accurate and stable behavior of the proposed algorithm which can accurately identify all transmission uncompensated and series-compensated line faults. The other advantage of this technique is that it can be used where multiple transmission lines are present.

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