A METHOD FOR THE CORRECT PROTECTION RESPONSE DURING POWER SYSTEM FAULTS SUBJECTED TO THE BAUCH'S PARADOX PHENOMENON

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ABSTRACT

False tripping is frequently blamed on incorrect settings or poor system models. However in many cases, it may be attributed to not uncommon phenomena, such as the so called "Bauch's paradox". In this paper the physical background of the Bauch's paradox phenomena will be explained. Based on this, a method for the correct response of distance protection under these extreme conditions is presented. Amongst others, this method consists of: the detection of the Bauch's paradox phenomena, optimised loop selection logic and a modified directional element. Chosen events recorded during distance protection test are used to illustrate the effectiveness of this method.

INTRODUCTION

The classical power system fault on the transmission/ distribution line is characterised by typical behavior in currents and voltages. In most cases, the voltages drop and currents increase in faulty phases/loops as well as the phase shift between currents and voltages is close to the angle line impedance $\underline{Z}_L$. These rather trivial properties are used successfully by the numerous protection functions guarantying a selective and reliable protection operation. Nevertheless in some network configurations combined with common network operation states the voltages and currents are not significant enough to recognize the faulty phases or loops. As a result the reliable operation in the protection function is not guaranteed. The extension of protection functions is necessary to recognize such untypical behaviour.

Bauch's paradox belongs to non classical fault transients. Therefore the recognition of the faulty loops/phases cannot be carried out using the traditional current/voltage pattern. In the case of Bauch's paradox, all currents are in the same electric phase and have the same magnitudes. Due to this fact, numerous protection algorithms cannot properly detect the faulty loop. In this paper, attention is paid to distance protection and its improvement in the case of Bauch's paradox.

PHYSICAL BACKGROUND OF THE BAUCH'S PARADOX

This phenomenon appears at a transmission or distribution line operating in a radial configuration. The strong, in-feed side does not need to be earthed. The second line side is solid earthed, has a weak in-feed and is connected with the other voltage level over a Star-Delta (Yd) grounding transformer. This configuration is very popular, especially if renewable dispersed energy sources are connected to the power system. The second condition for the phenomenon is the occurrence of the non-symmetrical fault with the earth connection. In figure 1, the condition for Bauch's paradox is illustrated. The current flow direction is marked using arrows. They also show relations between flowing currents.

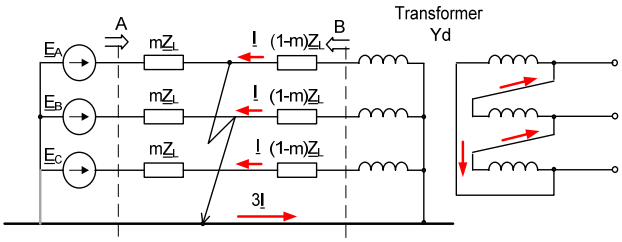

Figure 1: Equivalent circuit of the line under fault conditions (phase-to-earth fault during Bauch's paradox)

The configuration of the transformer from figure 1 allows for the propagation of the zero sequence component (represented as earth current), as presented in the equivalent circuit in the symmetrical component, based on figure 2. Since the very high magnetising, zero sequence impedance is connected to the leakage impedance of the secondary side the summarised impedance of the transformer (Yd) in zero sequence is relatively low. Therefore, due to unsymmetrical conditions the zero sequence current flows through transformer windings. Since the secondary windings are connected in Delta, the zero-sequence current cannot propagate outside of the transformer. This current circulates in secondary transformer windings, inducing currents on the primary side which are in phase and have the same magnitudes.

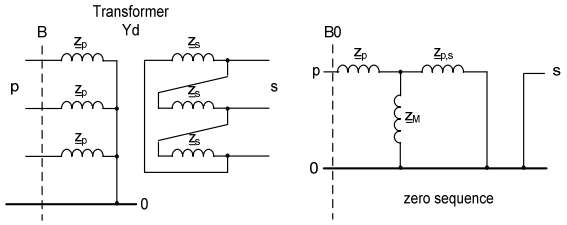

Figure 2: Star-Delta (Yd) grounding transformer 3-phase model.

Since the single phase-to-earth or double phase-to-earth fault contributes to a strong un-symmetry in the network with a high zero sequence voltage component, the zero sequence current is flowing into the network. In figure 3 the electric circuit for the single phase-to-earth fault is presented. The strong, in-feed side of the network is not earthed. This assumption does not limit the consideration subjected to Bauch's paradox but simplifies the understanding of the phenomenon.

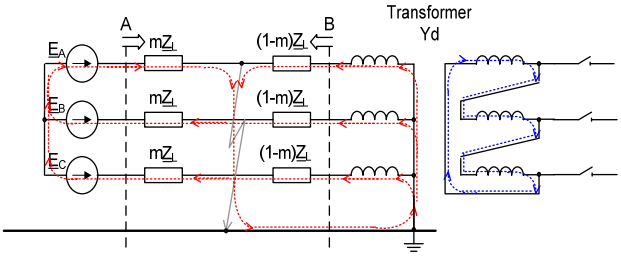

Figure 3: Single phase-to-earth fault during Bauch's paradox.

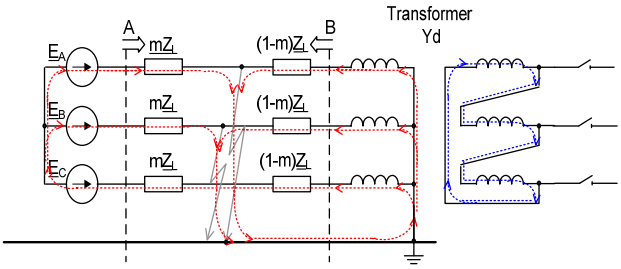

Figure 4: Double phase-to-earth fault during Bauch's paradox.

The single phase-to-earth fault causes the strong zero sequence voltage component. Since the strong, in-feed side is not grounded, the zero-sequence component can only propagate in transformer windings. Here it should be observed that zero sequence current can only be seen on side B of the network. Moreover the earth current is three times higher than the phase current. In figure 4, the circuit for the phase-to-phase with an earth fault is presented. Also, the strong distinct zero sequence current can be observed as well as similar effects, like the single phase-to-earth fault. The intensity of Bauch's paradox phenomenon depends on a number of network parameters:

- short circuit power of a strong, in-feed source,
- short circuit power of the transformer of the weak, in-feed side,
- network impedances including the impedance of the earth path,
- fault location.

THE BAUCH'S PARADOX IN SYMMETRICAL COMPONENTS

Through analysing the voltages and currents and based on the equivalent circuits from figure 3 and 4, it can be concluded that phase quantities deliver distorted patterns according to the fault type. For better handling of this problem the symmetrical components should be involved in what is described in this section.

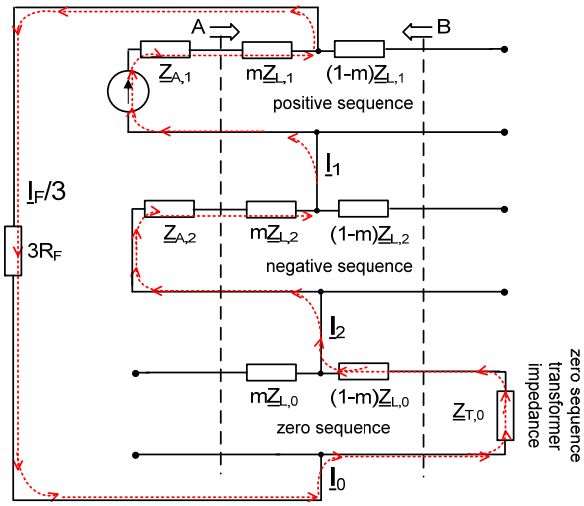

Figure 5: Current propagation in symmetrical components during single phase-to-earth fault (Bauch's paradox).

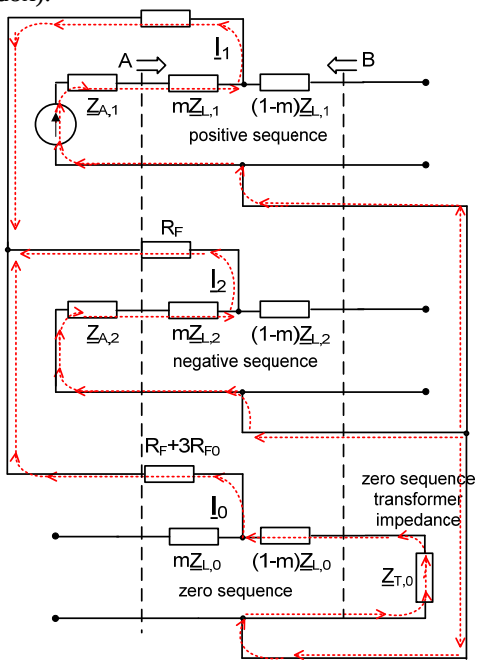

Figure 6: Current propagation in symmetrical components during double phase-to-earth fault (Bauch's paradox).

For both of these fault types, two different equivalent sequence circuits should be considered. In the case of single phase-to-earth faults, the sequence networks are connected to each other in series. It was assumed that the strong, in-feed side is not grounded. As a result, the zero sequence current of the strong, in-feed side A is not available. Due to the relatively low zero sequence impedance of the transformer, the fault current propagates through side B and can be measured there in zero sequence. The side A sees the fault current in negative and positive sequence. Because of that, only side B will recognize the phenomenon of Bauch's paradox. If the fault is located outside of the line, in the direction of the strong, in-feed side, both sides will experience Bauch's paradox. In the case of the external fault in the direction of the transformer, neither side experiences Bauch's paradox. Based on figure 5 and 6 it can be observed that side B does not measure negative or positive sequence. Due to this fact, only zero sequence can be used for the detection of the fault.

IMPACT ON DISTANCE PROTECTION

During Bauch's paradox the conventional distance protection algorithm can show some weaknesses, as mentioned here:

In case of the single phase-to-earth fault computed impedance of non-faulty loop (apparent impedance) can lie in the so called operating polygon. It results from a significant earth current. In addition the conventional direction element can show the wrong direction result. It can contribute to an unselective or delayed trip.

In the case of the phase-to-phase earth fault, the preferred double phase loop impedance cannot be computed, because the difference between phase currents is zero. For the fault handling, the 2 single phase-to-earth loops and their impedances must be involved. This has negative consequences on determining the direction using directional elements. Namely one of the single phase loops determines the forward fault direction. The second single phase loop recognizes the reverse fault direction. It contributes to the unacceptable sequential or unselective trip. Moreover, due to low load flow, it can happen that the preferred double phase impedance are calculated, delivering a random result.

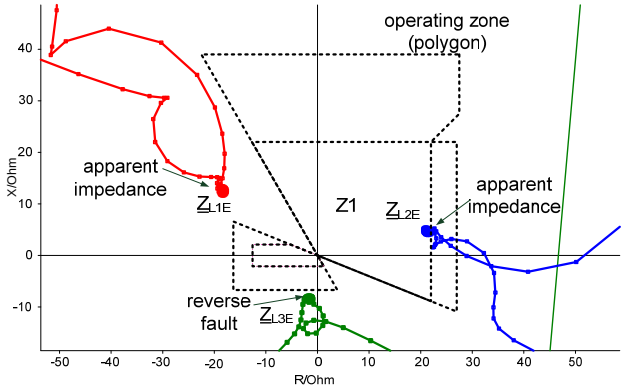

Figure 7: Impedance trajectories during single phase-to-earth fault with Bauch's paradox.

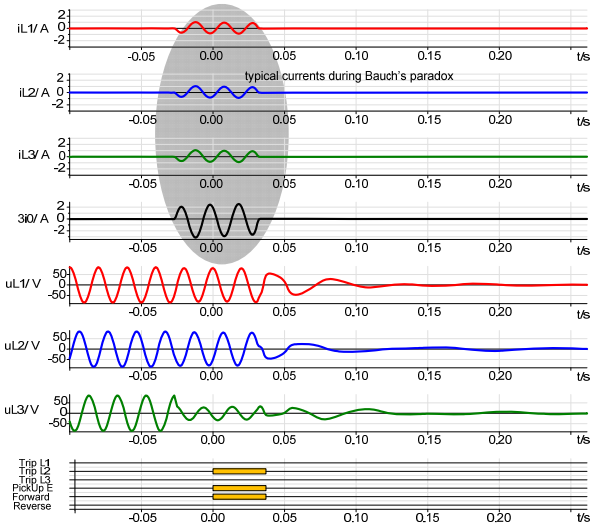

Figure 8: Response of a classical distance protection during a reverse single phase-to-earth fault with Bauch's paradox. One can observe that the distance protection determines a wrong loop and as a consequence, measures the wrong fault direction.

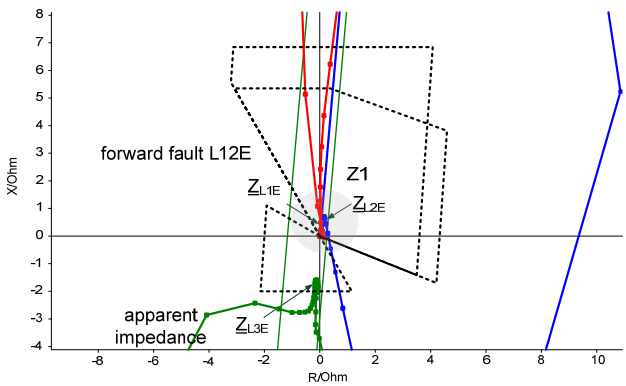

Figure 9: Impedance trajectories during double phase-to-earth fault with Bauch's paradox.

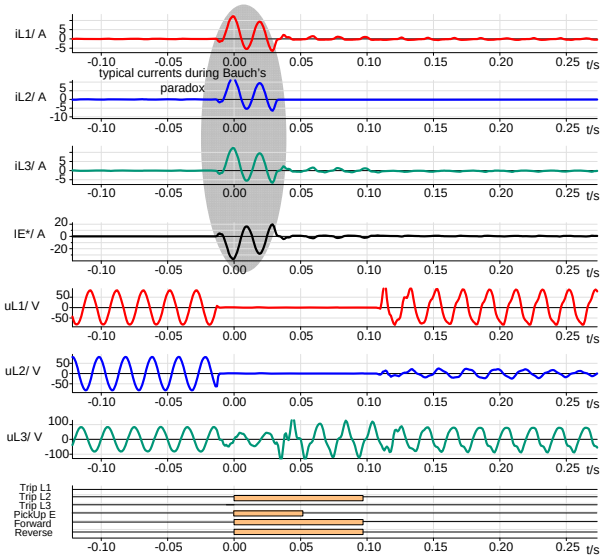

Figure 10: Response of a classical distance protection during a forward double phase-to-earth fault with Bauch's paradox. One can observe that distance protection detects the single-phase-to-earth fault and does not clear disturbance completely. The direction results are not plausible.

OPTIMIZATION ON DISTANCE PROTECTION

After considering the Bauch's paradox in symmetrical components, it can be concluded, that zero sequence quantity is a basis for detection of a faulty loop, as well as for determining a fault direction. Firstly, the Bauch's paradox effect must be detected. It is proposed that the zero sequence current is compared with the positive and negative sequence. If the zero sequence current is significantly higher than both other components, then the Bauch's paradox can be assumed. Mathematically it can be expressed in the following way:

$$\left|3\underline{I}_0\right| > k \cdot \left|3\underline{I}_1\right|, \quad \left|3\underline{I}_0\right| > k \cdot \left|3\underline{I}_2\right| \qquad (1)$$

where k>>1 is a comparison factor. This factor allows for detection of the Bauch's paradox even if a load flow at the considered line takes place.

In order to confirm Bauch's paradox definitively, the zero sequence current is compared to the phase currents. The comparison takes place based on the magnitudes only. The requirement according to the equaled electric phases of the flowing currents during Bauch's paradox is covered during comparison with the symmetrical components. Following expressions describe the comparison process with a zero sequence:

$$\begin{aligned} k_U\left|\underline{I}_A\right| &< \left|\underline{I}_0\right| < k_O\left|\underline{I}_A\right|, \\ k_U\left|\underline{I}_B\right| &< \left|\underline{I}_0\right| < k_O\left|\underline{I}_B\right|, \\ k_U\left|\underline{I}_C\right| &< \left|\underline{I}_0\right| < k_O\left|\underline{I}_C\right|, \end{aligned} \qquad (2)$$

where ku and ko are the appropriate limits, which test if the currents are in the assumed range, signifying Bauch's paradox.

After detection of the phenomenon the faulty loop must be determined. As a result the symmetrical components for voltage are involved. After considering the figure (double phase-to-earth fault), one can conclude that for this fault type, the negative and positive sequence voltages are equal. In order to determine the faulty loop, the phasor comparison between negative and positive sequences must be carried out. Since in conventional approach for symmetrical components one phase is considered as the reference phase, the difference between both phasor components can be 0°, 120° or 240°. For a simplification in approach, the computed negative sequence voltage is rotated additionally by 120° and 240° degrees. Thus, three differences are created and only one corresponds to the faulty loop:

$$\begin{aligned} &\left|\underline{U}_1 - \underline{U}_2\right| \approx 0 \ \vee \\ &\left|\underline{U}_1 - e^{j120°}\underline{U}_2\right| \approx 0 \ \vee \ \left|\underline{U}_1 - e^{j240°}\underline{U}_2\right| \approx 0 \end{aligned} \qquad (3)$$

where $\underline{U}_1$ and $\underline{U}_2$ are positive and negative sequence voltages respectively. The exponential complex component represents the phase shift.

Since measurement errors are possible and load flow takes place on the line, the difference between positive and negative component can deviate from 0. Due to this fact it is recommended to calculate an adaptive difference limit in dependence from both considered components. To this end, we propose the following equation:

$$m \cdot \max(\left|\underline{U}_1\right|, \left|\underline{U}_2\right|) + M \qquad (4)$$

where m and M are a percent factor and constant threshold respectively. If the criteria from formula 3 is not fulfilled the single phase-to-earth fault is detected in the loop, where the measured phase-to-earth voltage is lowest.

As mentioned during the Bauch's paradox phenomenon, the directional element cannot operate loop-oriented. For a fault direction determination, the zero sequence current and voltage must be involved. This means that, independent from the faulty loop, only one directional element based on the zero sequence is applied. The characteristic for the fault direction is presented in figure 11.

The idea of the zero sequence direction measurement consists in analysing the membership of the voltage and current phasors on the complex plane. For the forward fault, it is expected that both phasors are located in the first quadrant of the complex plane. If the reverse fault occurred, the phasors are placed in the third quadrant. A low deviation in phasor localisation according to quadrant membership is allowed.

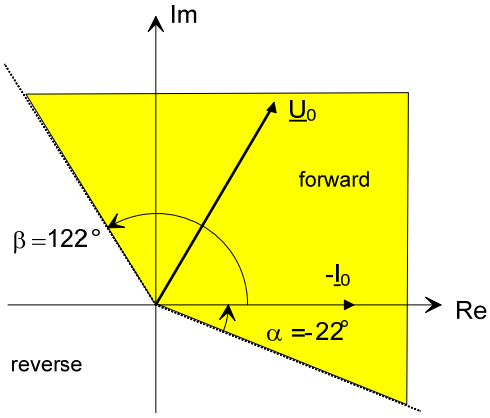

Figure 11: The directional characteristic with zero-sequence component.

RESULTS AND SUMMARY

The experimental tests of the proposed algorithm were performed on a digital relay. The typical high-voltage radial feeder with both strong and weak in-feed side (connected to Yd transformer) was modelled. The different faults were simulated in order to prove the behaviour of the device. The responses of the device on typical faults were as expected. Also in the case of the fault during Bauch's paradox, device behaviour was satisfying. In this paper we presented three fault cases with the responses of the digital relays.

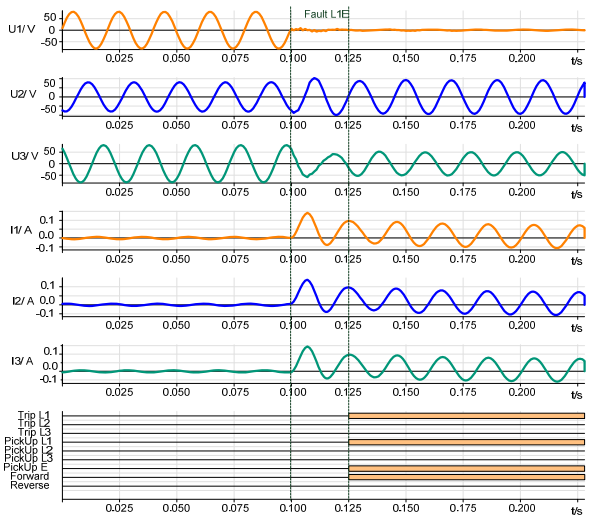

Figure 12: Single phase-to-earth fault in forward direction with Bauch's paradox. Optimized distance protection algorithm indicates correct loop and trip.

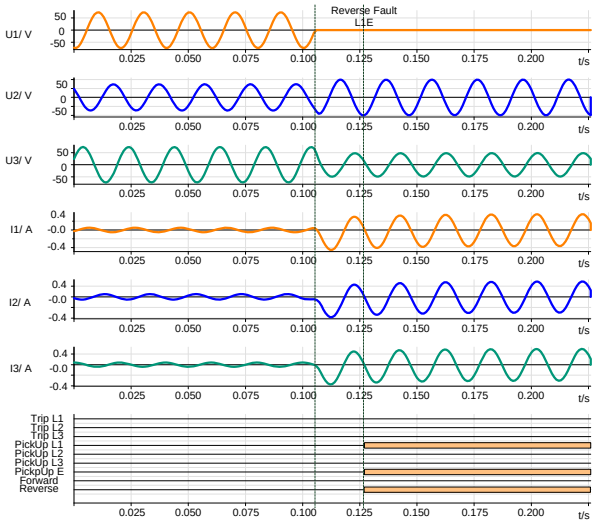

Figure 13: Single phase-to-earth fault in reverse direction with Bauch's paradox. Optimized distance protection algorithm indicates correct loop and does not trip.

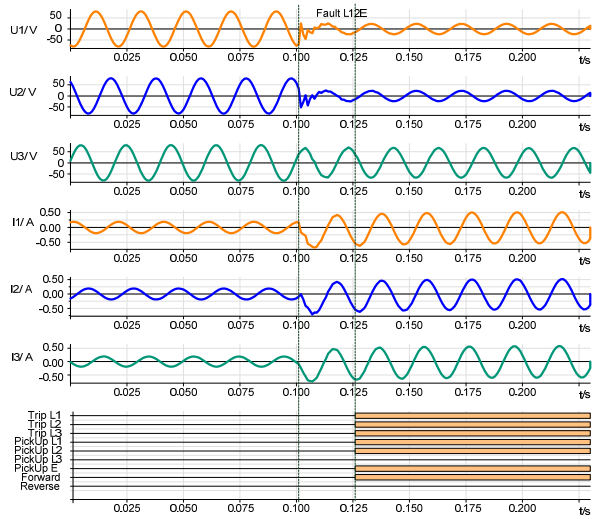

Figure 14: Double phase-to-earth fault in forward direction. Optimized distance protection algorithm indicates correct loop and trip.

REFERENCES

[1] C. Dzienis, M. Kereit, G. Steynberg and M. Claus, 2014, "Behandlung von Netzfehlern mit Bauch'schem Paradoxon", *STE ETG Konferenz*

[2] G. Ziegler, 2008, *Distanzschutz, Grundlagen und Anwendungen*, Siemens AG, Berlin, Germany.

[3] A. Hochrainer, 1957, *Symmetrische Komponenten in Drehstromsystemen*, Springer, Berlin, Germany.

[4] R. Roeper, 1985, *Short Circuit Currents in Three-phase Systems*, John Wiley and Sons, Berlin, Germany.