Electric Power Systems Research 119 (2015) 218–227

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Probabilistic assessment of new time-domain distance relay algorithms

Siniša J. Zubić [a,*], Milenko B. Djurić [b], Čedomir V. Zeljković [a]

[a] *Faculty of Electrical Engineering, University of Banjaluka, Patre 5, 78000 Banjaluka, Bosnia and Herzegovina*
[b] *Faculty of Electrical Engineering, University of Belgrade, Bulevar Kralja Aleksandra 73, 11120 Belgrade, Serbia*

ARTICLE INFO

Article history:
Received 10 May 2014
Received in revised form
26 September 2014
Accepted 4 October 2014
Available online 25 October 2014

Keywords:
Relay tripping time
Computational burden
Polygonal operating characteristic

ABSTRACT

In this paper we propose novel distance relay algorithms and a new test methodology for assessing the *security* and *dependability* of protective relay operations. The proposed algorithms with a polygonal operating characteristic are based on a time-domain phase comparator and compared to an algorithm based on discrete Fourier transformation (DFT), which is considered as a classical solution in this area.

Algorithms are usually tested on the worst case scenarios which purpose is to check if the algorithm would maloperate under some conditions and this kind of tests is necessary considering the enormous economic damage in case of power system blackouts. However, this approach is not enough for comparison of different algorithms if each of them passed those tests. Every comparison based on our choice of the test cases is in some way subjective and is not enough for assessment of security, dependability and average tripping time. In order to avoid a subjective selection of the simulation parameters we propose a probabilistic approach where the real frequency of some network conditions is considered using the probability density functions of the main variables measured in a real power system. The security, dependability and the relay tripping time are evaluated through a few thousand fault simulations and comparisons of the algorithms are presented in the paper. The proposed testing model can be adjusted to any transmission network if appropriate data is available.

1. Introduction

Power transmission lines are exposed to various types of faults and distance relays perform a vital role in their protection. In order to detect the fault, the most distance relays estimate the fundamental frequency phasors using some of the well-known methods such as the full cycle discrete Fourier transformation (FCDFT) [1], least error squares (LES) [2] and discrete wavelet transformation (DWT) [3]. Instead of the phasor-domain approach, there are also algorithms that detect the fault in the time-domain, processing the raw voltage and current samples without extracting their fundamental harmonics. In [4–6], a time-domain algorithm based on a characteristic of an electromechanical cylinder unit is introduced, while [7] presents an algorithm that uses a simple phase comparator based on the average power. Due to the simplicity, both algorithms implement a cross-polarized MHO characteristic that is not able to detect faults with high fault resistances.

In order to achieve a better fault resistance coverage we developed novel distance relay algorithms with polygonal operating characteristics based on the time-domain phase comparison principle. Calculating the phase difference in the time-domain, we are able to detect the fault using a smaller number of mathematical operations. In this paper three novel distance relay algorithms are tested and compared to an algorithm based on the phasor-domain approach with full-cycle DFT.

The Final Report of the August 14, 2003 blackout [8] concludes that the cascading outage was triggered by the unwanted operation of distance relays. The blackout affected more than 50 million people and resulted in a total economic loss between $7 and $10 billion [9]. This is one of the reasons why it is highly important for a protective relay system to operate when required (which is measured by dependability) and not to operate incorrectly (which is measured by security). Algorithms are usually tested in a classical deterministic way, through changing some variables in simulation over a wide range. By this approach it is possible to detect some of the worst case scenarios and adjust the relay settings in order to avoid the maloperation. The main weakness of this approach is that it is not possible to compare different algorithms if each of them passed the worst case scenarios. Every comparison based on our choice of the

* Corresponding author. Tel.: +48 511 739 220.
E-mail addresses: zubic.s@gmail.com (S.J. Zubić), mdjuric@etf.rs (M.B. Djurić), cedomir@etfbl.net (Č.V. Zeljković).

http://dx.doi.org/10.1016/j.epsr.2014.10.007
0378-7796/

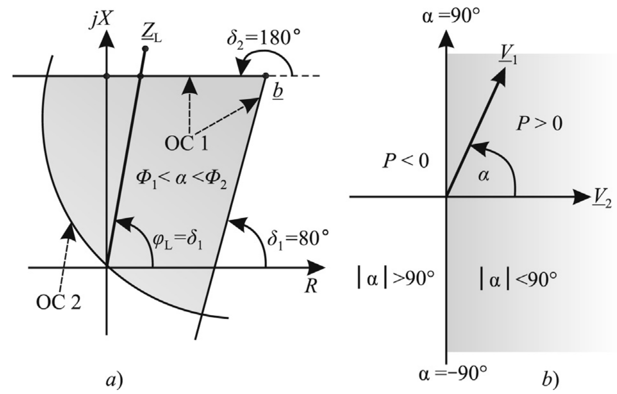

Fig. 1. (a) Z – plane representation of the polygonal operating characteristics, (b) border angles of the time-domain phase comparator based on the average power.

test cases is in some way subjective, emphasizing some scenarios that are rare in the real networks. The second problem is that security and dependability are not exactly assessed despite being the most important features of distance protections. The papers where the dependability and security are assessed are rare [10–12].

We collected data from transmission systems in Bosnia and Herzegovina, as well as Serbia and made a stochastic power system model based on the measured probability density functions. Using those data and running thousands of fault simulations it is possible to calculate the exact values of security, dependability and the average tripping time as well as recommend the optimal distance relay reach in R-direction. The proposed probabilistic testing methodology enables a more objective comparison of the algorithms because it avoids a subjective selection of the simulation parameters. The probabilistic methodology is easily adjusted to any transmission network subject to the availability of appropriate data. Many tests with different relay reach settings are conducted to compare the proposed algorithms to the phasor-domain algorithm based on the full-cycle discrete Fourier transformation.

2. Distance relay algorithms based on the phase comparison principle

It is convenient to display the operating characteristic for distance protection in the complex R–X plane (Fig. 1a). Distance relays operate when measured impedance enters inside the operating characteristic. Instead of calculating the impedance and checking if it entered inside the operating characteristic, distance relays usually detect a fault by comparing phase angles of the appropriate phasors $\underline{V}_1$ and $\underline{V}_2$ [13]. The phase comparison principle has been well known for many years and is based on the following equations:

$$\underline{V}_1 = \underline{k}_1 \cdot \underline{U}_r + \underline{k}_2 \cdot \underline{I}_r \quad (1)$$

$$\underline{V}_2 = \underline{k}_3 \cdot \underline{U}_r + \underline{k}_4 \cdot \underline{I}_r \quad (2)$$

Phasors $\underline{U}_r$ and $\underline{I}_r$ are functions of the phase voltages and currents on the protected transmission line. Those functions are dependent on the type of fault according to Table 1. The fault is detected if the phase difference between $\underline{V}_1$ and $\underline{V}_2$, labeled as α, is:

$$\Phi_1 \le \alpha \le \Phi_2 \quad (3)$$

Border angles Φ_1 and Φ_2, and coefficients $\underline{k}_1$–$\underline{k}_4$, determine the shape of the operating characteristic. The common approach in determining whether angle α meets the condition (3) is to calculate phasors $\underline{U}_r$, $\underline{I}_r$, $\underline{V}_1$ and $\underline{V}_2$. In [7] is shown that the same result can be obtained by using a simple phase comparator in the time domain. Signals are compared using their raw samples, without calculating phasors, which significantly decreases the computational burden.

Table 1
Inputs to a distance relay.

Type of fault	$\underline{U}_r$	$\underline{I}_r$
a–g	$\underline{U}_a$	$\underline{I}_a + \underline{k}_0\underline{I}_0$
b–g	$\underline{U}_b$	$\underline{I}_b + \underline{k}_0\underline{I}_0$
c–g	$\underline{U}_c$	$\underline{I}_c + \underline{k}_0\underline{I}_0$
a–b	$\underline{U}_a - \underline{U}_b$	$\underline{I}_a - \underline{I}_b$
b–c	$\underline{U}_b - \underline{U}_c$	$\underline{I}_b - \underline{I}_c$
c–a	$\underline{U}_c - \underline{U}_a$	$\underline{I}_c - \underline{I}_a$

a, b, c – phases; g – ground; k_0 is a relay setting called residual compensation factor.

In [7], a circular operating characteristic is implemented due to simplicity, however in practice, it is more common to make use of a polygonal operating characteristic as it has better fault resistance coverage. In the next section, we demonstrate how to implement a polygonal operating characteristic in the time domain.

3. An optimal polygonal operating characteristic in the time-domain

Operating characteristic OC1, shown in Fig. 1a, can be obtained by using the next two equations:

$$\underline{V}_1 = \underline{k}_1 \cdot \underline{U}_r + \underline{k}_2 \cdot \underline{I}_r = k_1 e^{-i\beta 1} \cdot \underline{U}_r + k_2 e^{-i\beta 2} \cdot \underline{I}_r \quad (4)$$

$$\underline{V}_2 = \underline{k}_4 \cdot \underline{I}_r = k_4 e^{-i\beta 4} \cdot \underline{I}_r \quad (5)$$

The line impedance is shown as a solid line stretching from the origin to the point labeled $\underline{Z}_L$, and the angle of the line impedance is labeled φ_L. We set the relay reach by choosing $\underline{b}$, while it is common to set $\delta_2 = 180°$, $\delta_1 = \varphi_L$. In order to achieve the operating characteristic shown in Fig. 1a, five unknown parameters Φ_1, Φ_2, $\underline{k}_1$, $\underline{k}_2$, $\underline{k}_4$ have to satisfy the next three equations:

$$\underline{k}_2 = -\underline{b} \cdot \underline{k}_1 \quad (6)$$

$$\Phi_1 = \delta_2 + \beta 1 - \beta 4, \quad (7)$$

$$\Phi_2 = \delta_1 + \beta 1 - \beta 4 + 180°. \quad (8)$$

That means that we have freedom to choose two parameters, while Eqs. (6)–(8) determine three. The main difference between the time-domain approach and the phasor domain approach is that, in the time-domain approach, values of the five parameters affect the fault detection time. The main reason for that are arguments of the complex numbers, $\underline{k}_1$, $\underline{k}_2$, $\underline{k}_4$. If we write Eqs. (4) and (5) in the time-domain, then arguments $\beta 1$, $\beta 2$ and $\beta 4$ present the time delays labeled as N_1, N_2 and N_4:

$$v_1(n) = k_1 \cdot u_r(n - N_1) + i_r(n - N_2) \quad (9)$$

$$v_2(n) = k_4 i_r(n - N_4) \quad (10)$$

Number n represents the nth sample, while N_i depends on m which is the number of samples per fundamental cycle T_f:

$$N_i = \frac{\beta i}{360°} m. \quad (11)$$

We have to choose N_i as an integer that is the closest to the value obtained by Eq. (11).

Larger value N_i causes larger fault detection time, because the algorithm does not use the latest signal samples. This is the reason why it is important to choose optimal values of $\underline{k}_1$, $\underline{k}_2$ and $\underline{k}_4$. In order to get minimal time delays the first rule is choosing the coefficients with minimal arguments βi. The best choice is zero, but 180° also does not cause any time delay because it can be obtained by multiplying the coefficient by −1. If the nonzero values βi are inevitable, then we choose a larger $\beta 1$ than $\beta 2$ and $\beta 4$. The reason is that the time shift in the current signal has a larger impact on the fault detection time, since the rate of change in currents, at the moment of a fault, is larger than the change in voltages.