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Digital Line Differential Protection Using Symmetrical Components

T. ŁOBOS
Department of Electrical Engineering, Technical University of Wroclaw, Wyb. S. Wyspianskiego 27, 50-370 Wroclaw (Poland)
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ABSTRACT

A new method for digital line differential protection is presented. The protection compares the time function and the orthogonal function of the symmetrical positive-sequence component at the input and output of a transmission line. From these values the magnitude of the differential current is evaluated. The time function is calculated according to the SD4c algorithm and the orthogonal function according to the SD4s algorithm from four sampled triplets. The first results of the investigation are shown. By using this method, a phase-independent operating time of less than half a period can be obtained.

1. INTRODUCTION

Analog line differential protection is by no means perfect. To reduce the number of pilot wires, summation auxiliary current transformers (CTs) with various mixing ratios have been used [1, 2]. The output signals of the CTs from the input and output of the protected transmission line have been compared. The sensitivity of the protection with summation CTs is not equal for all phases.

A lot of research has been carried out on the application of microcomputer technology to power system control, monitoring and protection. The digital technique offers new possibilities. New relays should not reproduce existing criteria, but ought to use new ones which make protection faster and more sensitive [3]. The method of symmetrical components (zero-, positive- and negative-sequence; 0, 1, 2) is one of the basic tools for the analysis of three-phase power systems. Fast estimation of the symmetrical components from sampled signals can be used efficiently for control and protection tasks in electrical power systems [4 - 6]. This paper presents a new method of digital line differential protection using symmetrical components.

2. FAST ALGORITHMS FOR DETERMINATION OF SYMMETRICAL COMPONENTS

The relations between phase quantities $\mathbf{G}_R, \mathbf{G}_S, \mathbf{G}_T$ and the symmetrical components $\mathbf{G}_0, \mathbf{G}_1, \mathbf{G}_2$ are given by

$$\begin{bmatrix}\mathbf{G}_0\\ \mathbf{G}_1\\ \mathbf{G}_2\end{bmatrix} = \frac{1}{3}\begin{bmatrix}1 & 1 & 1\\ 1 & \mathbf{a} & \mathbf{a}^2\\ 1 & \mathbf{a}^2 & \mathbf{a}\end{bmatrix}\begin{bmatrix}\mathbf{G}_R\\ \mathbf{G}_S\\ \mathbf{G}_T\end{bmatrix} \tag{1}$$

In eqn. (1), $\mathbf{a}$ represents a phase-rotating operator

$$\mathbf{a} = \exp\left(\mathrm{j}\,\frac{2\pi}{3}\right); \qquad \mathbf{a}^2 = \exp\left(\mathrm{j}\,\frac{4\pi}{3}\right) \tag{2}$$

The time functions of the phase quantities g_R, g_S, g_T and their corresponding complex phasors are given by:

$$g_R = \hat{g}_R \cos(\omega t + \varphi_R)$$

$$g_S = \hat{g}_S \cos(\omega t + \varphi_S)$$

$$g_T = \hat{g}_T \cos(\omega t + \varphi_T) \tag{3a}$$

$$\mathbf{G}_R = \hat{g}_R \exp(\mathrm{j}\varphi_R)$$

$$\mathbf{G}_S = \hat{g}_S \exp(\mathrm{j}\varphi_S)$$

$$\mathbf{G}_T = \hat{g}_T \exp(\mathrm{j}\varphi_T) \tag{3b}$$

From eqns. (3) it follows that the time (cosine) function can be found from

$$g_i^c = \mathrm{Re}[G_i \exp(\mathrm{j}\omega t)] \tag{4}$$

Applying expressions (3b) to (1) and then using eqn. (4) we find the time representation of

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the symmetrical components:

$$3g^c_{1,2} = \hat{g}_R \cos(\omega t + \varphi_R) - \frac{1}{2}[\hat{g}_S \cos(\omega t + \varphi_S) + \hat{g}_T \cos(\omega t + \varphi_T)] \mp \frac{\sqrt{3}}{2}[\hat{g}_S \sin(\omega t + \varphi_S) - \hat{g}_T \sin(\omega t + \varphi_T)] \quad (5)$$

The orthogonal (sine) function can be found from

$$g^s_i = \mathrm{Im}[G_i \exp(j\omega t)] \quad (6)$$

Using eqn. (6) we can find the time representation of the orthogonal (sine) function of the symmetrical components:

$$3g^s_{1,2} = \hat{g}_R \sin(\omega t + \varphi_R) - \frac{1}{2}[\hat{g}_S \sin(\omega t + \varphi_S) + \hat{g}_T \sin(\omega t + \varphi_T)] \pm \frac{\sqrt{3}}{2}[\hat{g}_S \cos(\omega t + \varphi_S) - \hat{g}_T \cos(\omega t + \varphi_T)] \quad (7)$$

In eqns. (5) and (7) the terms $\hat{g}\cos(\omega t + \varphi)$ and $\hat{g}\sin(\omega t + \varphi)$ can be calculated from two or more sampled values. Applying the addition theorem we obtain, for the time point t_k,

$$\hat{g}\sin(\omega t_k + \varphi) = -\frac{g_{k+1} - g_{k-1}}{2\sin\Delta} \quad (8a)$$

$$\hat{g}\cos(\omega t_k + \varphi) = \frac{1}{2\sin^2\Delta}(-g_{k-2} + g_{k-1}\cos\Delta + g_k - g_{k+1}\cos\Delta) \quad (8b)$$

where $\Delta = 2\pi/N$ and N is the number of samples in one cycle of the basic component.

Now we can apply the expressions (8) to (5) and (7). In this way, we obtain formulae for the time (cosine) function of the symmetrical components (called the SD4c method),

$$3g^c_{1,2k} = \frac{1}{2\sin^2\Delta}\bigg[(g_{Rk} - g_{Rk-2}) - (g_{Rk-1} - g_{Rk-1})\cos\Delta - \frac{1}{2}(g_{Sk} - g_{Sk-2} + g_{Tk} - g_{Tk-2}) + (g_{Sk-1} - g_{Sk-1})\cos\left(\Delta \mp \frac{\pi}{3}\right) + (g_{Tk+1} - g_{Tk-1})\cos\left(\Delta \pm \frac{\pi}{3}\right)\bigg] \quad (9)$$

and for the orthogonal (sine) function (called the SD4s method),

$$3g^s_{1,2k} = \frac{1}{2\sin^2\Delta}\bigg[(g_{Rk-1} - g_{Rk+1})\sin\Delta \mp \frac{\sqrt{3}}{2}(g_{Sk-2} - g_{Sk}) - (g_{Sk-1} - g_{Sk+1})\sin\left(\Delta \mp \frac{\pi}{3}\right) \pm \frac{\sqrt{3}}{2}(g_{Tk-1} - g_{Tk}) - (g_{Tk-1} - g_{Tk+1})\sin\left(\Delta \pm \frac{\pi}{3}\right) \quad (10)$$

To examine the filter properties of the design methods the frequency characteristics have been investigated. For each formula the transfer properties in the frequency domain between the phase values g_{RST} at the input and the positive-sequence component g_1 at the output have been analysed. Figure 1 shows the frequency characteristics. From these characteristics it follows that the DC component ($f = 0$) and the harmonics $\nu = 0.5kf_S/f_1$ ($k = 1, 2, \ldots$) are filtered out.

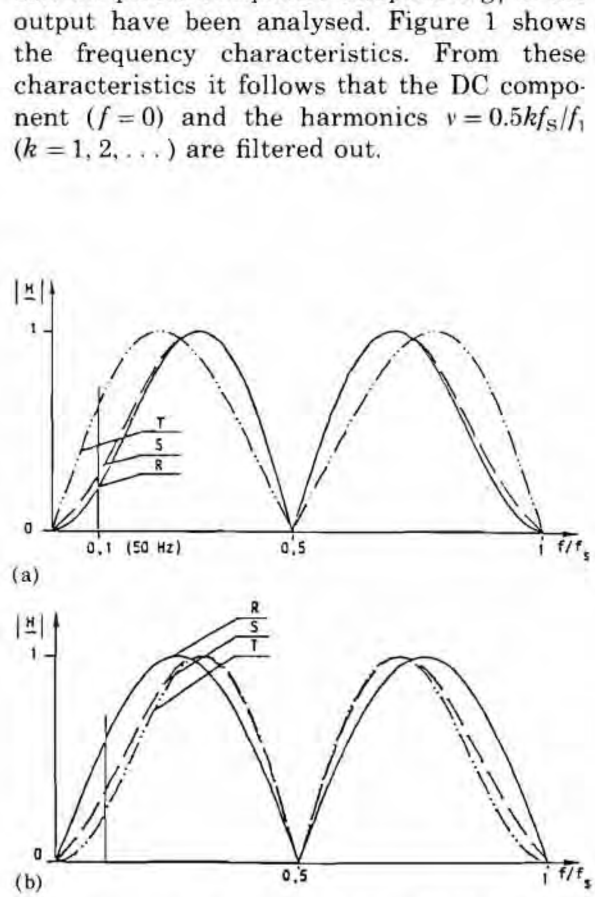

Fig. 1. Frequency characteristics of (a) the SD4c and (b) the SD4s method.

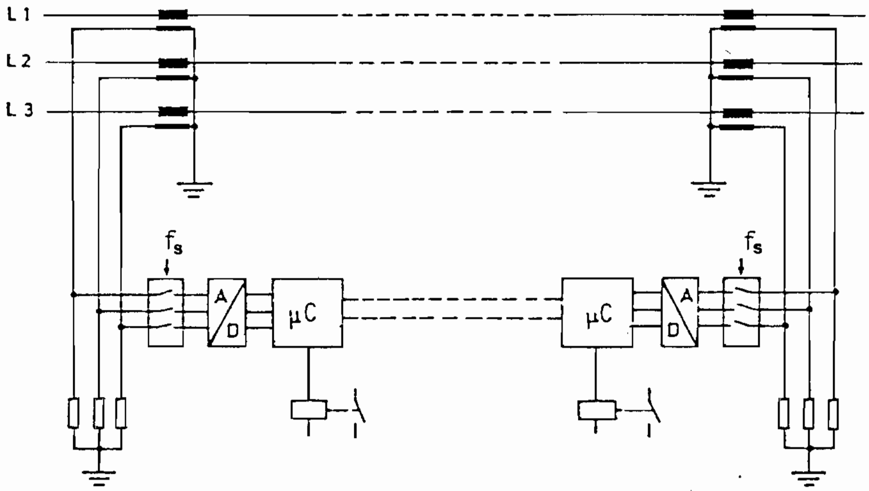

Fig. 2. Digital differential line protection.

3. LINE DIFFERENTIAL PROTECTION

The new concept of the line differential protection has been implemented by using the Siemens microcomputer system SMP with microprocessors 8088 and 8087 (Fig. 2) [7]. The protection compares the time (cosine) function and the orthogonal (sine) function of the symmetrical positive-sequence component from the input and output of a transmission line. From these values the magnitude of the differential current is evaluated. The cosine function is calculated using the SD4c algorithm and the sine function with the SD4s algorithm. These algorithms need four successive sampled triplets and were implemented with a sampling frequency of 500 Hz. After each sampling cycle, in a time interval of 2 ms, the new updated values of the differential current are evaluated. By determining both the cosine and sine functions, it is possible to calculate the magnitude of the differential current immediately. For this reason the operating time of the protection is phase independent. The secondary currents of all CTs are filtered by additional recursive Bessel low-pass filters with the cut-off frequency $f_B = 120$ Hz and the sampling frequency $f_{Bs} = 1000$ Hz.

Each second value from the filter output is taken for evaluation by the SD4 methods. Figure 3 shows the resulting transfer function of the SD4c method (phase A) and the low-pass filter. The filters suppress the noise of the frequencies from 250 to 750 Hz. They increase the operating time of the protection by about 2 ms.

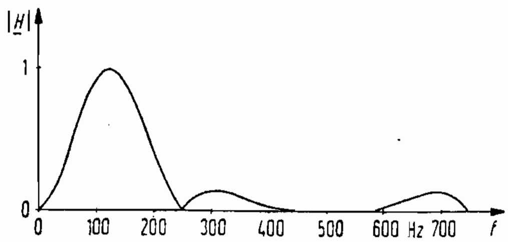

Fig. 3. Frequency characteristic of the combination of a Bessel low-pass filter ($f_B = 120$ Hz, $f_{Bs} = 1000$ Hz) and the SD4c method ($f_s = 500$ Hz, phase A).

4. INVESTIGATIONS

Investigations of line differential protection were carried out on the three-phase network model at the University of Erlangen. Various short-circuits on the 50 km, 220 kV transmission line were simulated. An order for tripping the breakers was given when three successive evaluated values of the differential current were greater than the current setting. The current waveforms during the three-phase short-circuits and during the two-phase to ground short-circuits are shown in Figs. 4 and 5, respectively. In all cases the operation time of the protection was phase independent and less than 8 ms.

It is possible to evaluate the differential current after each sampling cycle, in a time interval of 1 ms, taking for evaluation each second value from the output of the low-pass

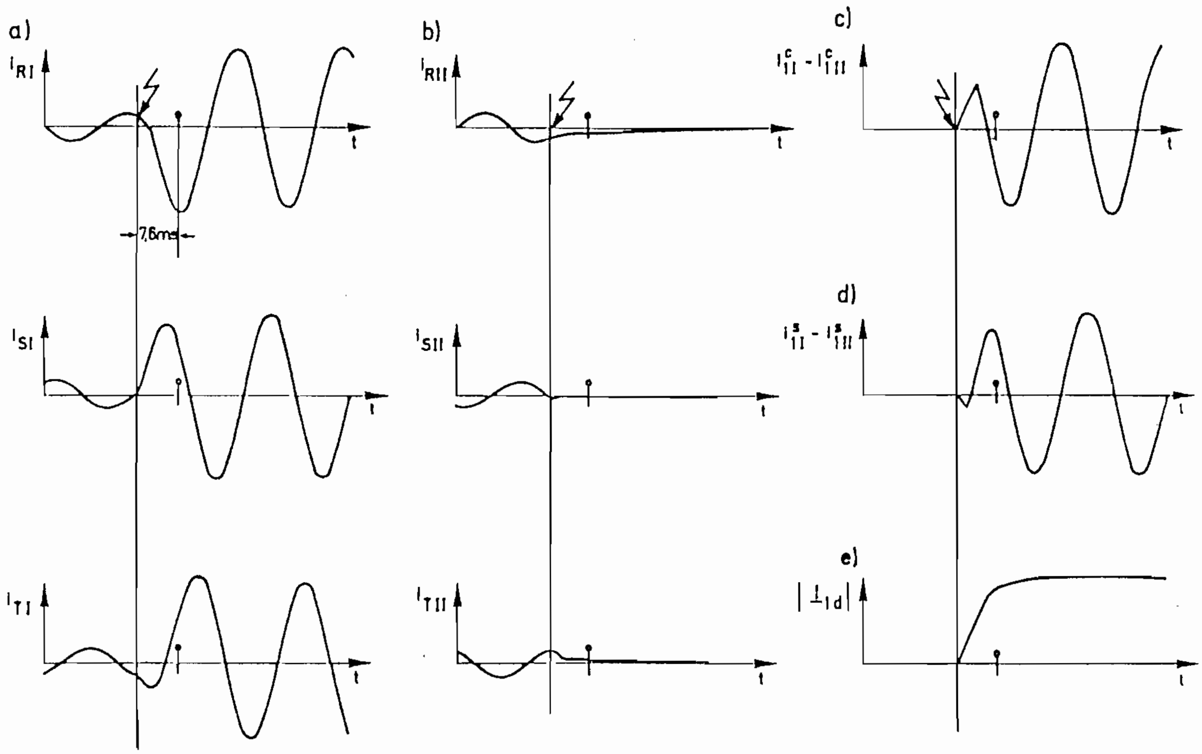

Fig. 4. Three-phase short-circuit on a line fed from one side: (a) phase currents at the sending end; (b) phase currents at the receiving end; (c) difference between the cosine functions of the positive-sequence components; (d) difference between the sine functions; (e) magnitude of the differential current. (↑ = tripping order.)

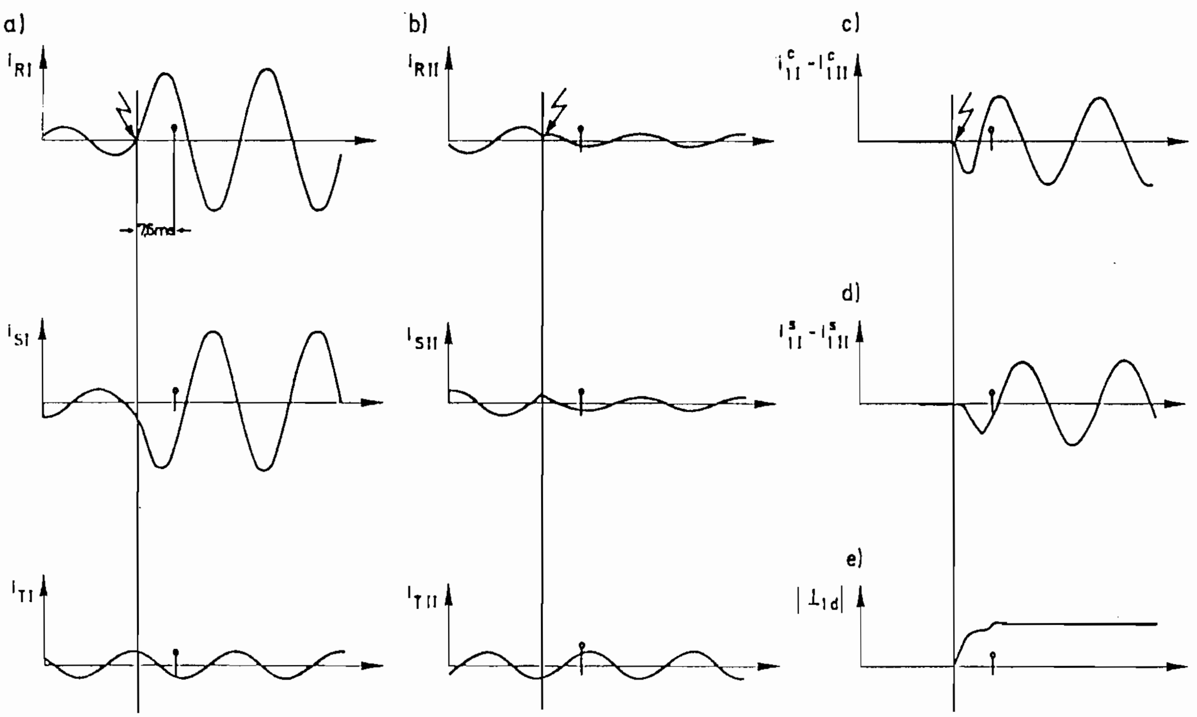

Fig. 5. Two-phase to ground short-circuit. (a) - (e) as in Fig. 4.

filter. In this way, we can decrease the operation time of the protection by almost 3 - 4 ms.

5. CONCLUSIONS

Digital signal processing offers new possibilities for control and protection tasks in electrical power systems. The fast estimation of the symmetrical components from sampled phase currents can be used efficiently for line differential protection. The sensitivity of the protection which uses symmetrical components is equal for all phases. By determining both the cosine and sine functions, the magnitude of the differential current can be calculated. For this reason the operating time of the protection is phase independent. By using the fast SD4 methods the operating time was less than 8 ms in all cases.

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