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A novel unit protective relaying concept based on current signal sequential overlapping derivative transform: Two sides fed transmission line application

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SOD transform;
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Abstract This paper presents a novel and accurate unit protective relaying concept for EHV transmission lines. The proposed protective concept implements a simple current signal sequential over lapping derivative, SOD transform to detect transmission line transient disturbances. It uses both polarity and magnitude of the first disturbance, arrived at relay location, to identify internal and external faults rapidly. The proposed unit protective relaying concept is applied to two sides fed transmission lines. The simulation results presented show that the protective concept is simple with high reliability, sensitivity and achieve an extra high speed relaying. In addition, it has immunity against the influence of the large capacitance of the line, the saturation of the current transformers and the synchronization problems.

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Contents

1. Introduction

The contemporary techniques for transmission line protection can be broadly classified into two categories, the non-unit and unit protection [1]. Non-unit protection, detecting a fault using only information obtained at one end, faults near the remote end cannot be cleared without the introduction of sometime delay. There is always an uncertainty at the limits of a protective zone. Unit protection, detecting fault using information obtained at the line ends, such as directional comparison, phase comparison, differential protection and pilot wire relays [2]. Differential protection scheme allows sensitive and precise detection of internal faults while ignoring other events such as external faults, load flow fluctuation, and power swings [3]. Application of the differential protection concept reveals several problems. Amongst these problems, the synchronization of phase currents at both ends presents a considerable constraint [4] and current transformer (CT) inaccuracies; in particular errors due to saturation of the core in the presence of decaying dc offset current [5,6]. Vector difference between the measured currents at the two ends of the transmission line is used for the operation of most current differential relays [7,8]. Ref. [9] uses the wavelet analysis for pilot differential relay.

One difficulty of the application of line protections to long transmission lines is the influence of the large capacitance of the line. When a fault occurs on a long line, relatively large magnitude harmonic components of current and voltage are superimposed on the fundamental frequency component due to the large capacitance of the line. This harmonic component can cause oscillation of the distance measurement. It is difficult to remove the harmonic component completely because the order of the harmonic component varies with several conditions. The order of the harmonic components varies with the fault point, source impedance, fault modes, etc. Therefore, to remove all unwanted harmonic components by a digital filter is very difficult [10]. Ref. [11] uses the distributed line model to consider line charging current.

Traveling waves was introduced for transmission-line protection with a different point of view to the conventional techniques. The cross-correlation function (CCF) is one of the first proposed techniques for fault detection in traveling-wave-based protection schemes. However, due to the wide expansion of power systems, the second traveling wave arriving at the relay location could be a combination of reflected waves from different discontinuity points in the power grid. This affects the correct identification of the fault point by using CCF. Some improved techniques that proposed overcoming this problem provide better performance especially for high-impedance faults. For most of these techniques, the data window length performs a determinative role on the performance of the protection scheme. Fixed data windows are not able to provide accurate and reliable identification of the propagating waves for all probable cases of close-in and distant faults. Meanwhile, the application of variable length data windows could provide better results. Directional protection using polarity of the first arriving voltage and current waves is another technique which can discriminate between forward and backward faults. This principle is immune to most of the uncertainties, which affect performance of the CCF-based techniques, and could rapidly identify internal faults using the information obtained at both ends of the transmission line [12].

This paper presents a novel and accurate unit protective relaying concept for EHV transmission lines. The proposed protective concept implements a simple current signal in sequential over lapping derivative, SOD transform [13], to detect transmission line transient disturbances. It uses both polarity and magnitude of the first disturbance, arrived at relay location, to identify internal and external faults rapidly. The proposed unit protective relaying concept is applied to the two sides fed transmission lines. The simulation results presented show that the protective concept is simple with high reliability, sensitivity and achieve an extra high speed relaying. In addition, it has immunity against the influence of the large capacitance of the line, the saturation of the current transformers and the synchronization problems.

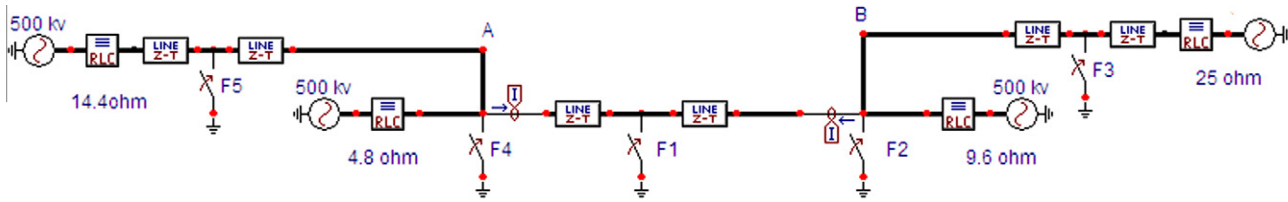

Figure 1 Two sides fed transmission line configuration system.

2. Configurations systems modeling

Fig. 1 shows the studied configuration system through out this paper, two sides fed transmission line. The system parameters are taken from the 500 kV Egyptian Unified Power System. The data are listed in Appendix A. The alternative transient program, ATP [14] is used to generate the current signals while the mathematical programming environment of MATLAB [15] is used to perform the suggested relaying analysis. As the suggested protective relaying concept is based on transient components associated with fault condition, the sampling frequency used in simulation studies is chosen to be 100 kHz.

3. Sequential overlapping derivative transform

The sequential overlapping derivative, SOD, is a derivative based concept. It succeeds to extracting any transient components associated with current and voltage signals. The SOD transform is acquired by using a simple first derivative of the processing signal. This process is sequentially done of a suitable window for the interested SOD order. The required order of the SOD will depend of the degree of accuracy. Table 1 illustrates the way of implementing the sequential overlapping derivative signals. The first column represents the processing order while the others columns represents the corresponding equation. The symbol Q represents the original signal, phase voltage or phase current, While, n is the instantaneous sample number.

3.1. General formula of the SOD

For convenience, a general equation of the SOD is described as follows:

$$S_m(n) = \sum_{j=1}^{j=m+1} (-1)^{j+1}(c_j)_m Q(n-j+1) \quad (1)$$

where m is the SOD order. $S_m(n)$ is the SOD transform signal of order m. $Q(n)$ is the original instantaneous signal, voltage or current accordingly. n is the instantaneous sample number of the original signal and it must start from $m+1$. $(C_j)_m$ are the multiplier coefficients of order m and are defined as follows:

- The first and the last multiplier coefficients $(c_1)_m$ and $(c_{m+1})_m$, are equal one.
- The second multiplier coefficients $(c_2)_m$, are equal the SOD order, m.
- The other multiplier coefficients of order m, can be calculated as follows:

$$(c_j)m = (c_j)_{m-1} + (c_{j-1})_{m-1} \quad (2)$$

It is important to mention that the SOD has the following interesting specification:

1. The sum of all coefficients is always equal zero, $\sum(-1)^{j+1}(c_j)_m = 0$.
2. The multiplier coefficients values $(c_j)_m$, are repeatable with a numerical series. For example, if the order is six, the series will be,

$$Q(n) - \mathbf{6}Q(n-1) + \mathbf{15}Q(n-2) - 20Q(n-3) + \mathbf{15}Q(n-4) - \mathbf{6}Q(n-5) + Q(n-6) \quad (3)$$

3.2. Choice of the SOD order, *m*

To select the proper order, the responses of the SOD transform are studied for normal and faulty conditions. Fig. 1 shows the studied configuration system to examine the effect of order on the SOD transform. Phase a current signal and the output signals of SOD transform for $m = 1, 2, 3$ and 4, (Si1, Si2, Si3 and Si4), for normal and faulty conditions are shown by Figs. 2 and 3 respectively.

By comparing the outputs of first, second, third and fourth SOD,

1. The fundamental and DC components die out in the third SOD, see Fig. 2.
2. Increasing the SOD order leads to amplify the extracted high frequency components magnitude, see Fig. 3.
3. The length of the processing SOD Window, numbers of samples, is dependent on the order m, see Table 1.

An extensive study showed that SOD transform successes to eliminate the fundamental and DC components and extracts the high frequency components at $m = 3$. Therefore, the authors suggest using the fourth order as an accurate solution.

4. Novel SOD unit protective relaying concept

The proposed SOD unit protective relaying concept is consisting of starting **criterion** in combination with internal/external discriminator **criterion**. The first **criterion detects** fault presence while the other **criterion** detects whether the fault is internal or external.

4.1. The starting criterion

The starting **criterion implements** the positive sequence quantity of the current signals, in the fourth SOD transform, to extract the transient components associated with

Table 1 SOD concept implementation.

SOD order	Input samples							
	$Q(n)$	$Q(n-1)$	$Q(n-2)$	$Q(n-3)$	$Q(n-4)$	$Q(n-5)$	$Q(n-6)$	. . ., etc
1st SOD	$Q(n) - Q(n-1)$	$Q(n-1) - Q(n-2)$	$Q(n-2) - Q(n-3)$	$Q(n-3) - Q(n-4)$	$Q(n-4) - Q(n-5)$	$Q(n-5) - Q(n-6)$	. . ., etc.	
2nd SOD	$Q(n) - 2Q(n-1) + Q(n-2)$	$Q(n-1) - 2Q(n-2) + Q(n-3)$	$Q(n-2) - 2Q(n-3) + Q(n-4)$	$Q(n-3) - 2Q(n-4) + Q(n-5)$	$Q(n-4) - 2Q(n-5) + Q(n-6)$	. . ., etc.		
3rd SOD	$Q(n) - 3Q(n-1) + 3Q(n-2) - Q(n-3)$	$Q(n-1) - 3Q(n-2) + 3Q(n-3) - Q(n-4)$	$Q(n-2) - 3Q(n-3) + 3Q(n-4) - Q(n-5)$	$Q(n-3) - 3Q(n-4) + 3Q(n-5) - Q(n-6)$	. . ., etc.			
4th SOD	$Q(n) - 4Q(n-1) + 6Q(n-2) - 4Q(n-3) + Q(n-4)$	$Q(n-1) - 4Q(n-2) + 6Q(n-3) - 4Q(n-4) + Q(n-5)$	$Q(n-2) - 4Q(n-3) + 6Q(n-4) - 4Q(n-5) + Q(n-6)$	. . ., etc.				
5th SOD	$Q(n) - 5Q(n-1) + 10Q(n-2) - 10Q(n-3) + 5Q(n-4) - Q(n-5)$	$Q(n-1) - 5Q(n-2) + 10Q(n-3) - 10Q(n-4) + 5Q(n-5) - Q(n-6)$	. . ., etc.					
6th SOD	$Q(n) - 6Q(n-1) + 15Q(n-2) - 20Q(n-3) + 15Q(n-4) - 6Q(n-5) + Q(n-6)$	. . ., etc.						
. . ., etc.	. . ., etc.	. . ., etc.	. . ., etc.	. . ., etc.	. . ., etc.	. . ., etc.	. . ., etc.	. . ., etc.

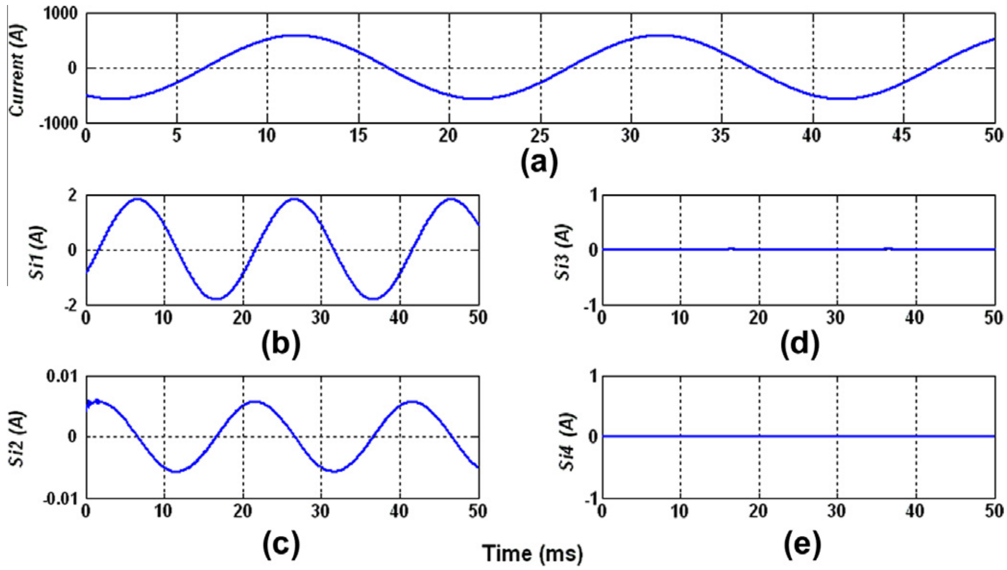

Figure 2 Phase current and SOD transform signals, (Si1, Si2, Si3 and Si4), for normal operation.

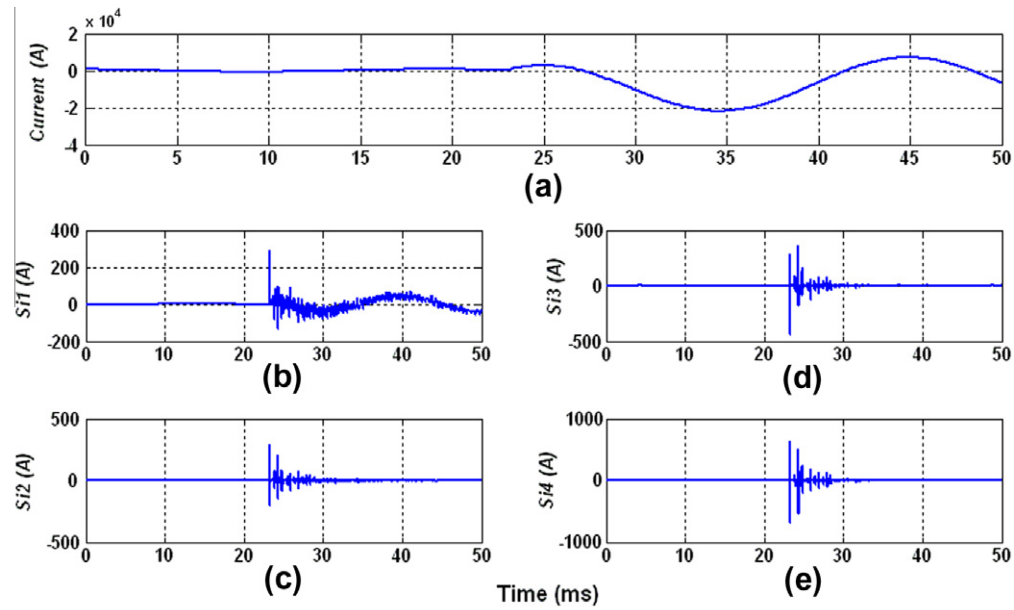

Figure 3 Phase current and SOD transform signals, (Si1, Si2, Si3 and Si4), for phase a to ground fault.

it. The mathematical formula for the real-time computation of the positive sequence components is given in the Appendix B. The fourth SOD signal as a function of the positive sequence quantity of the current signal and the sample numbers is described as follows:

$$SI(n) = I_1(n) - [4I_1(n-1)] + [6I_1(n-2)] - [4I_1(n-3)] + I_1(n-4) \quad (4)$$

where $I_1 = 3I_P$, I_P is the positive sequence quantity of the current signal. Fig. 4 shows the SOD transform response for single line to ground fault.

It is clear evident that, the SOD signal always lies around zero values during normal condition, and strongly deviates from zero in faulty conditions. The fault detection will be obtained as the absolute value of the *SI* signal becomes greater than a threshold limit. An adaptive threshold limit, ρ, is proposed, here, to be a function of the sampling frequency and SOD order, m, as follows:

$$\rho = (m+1)/f_s \quad (5)$$

where f_s is the processing sampling frequency in kHz. The proposed threshold limit is examined for various sampling frequency, from 50 kHz to 600 kHz. Table 2 summarized the values of the threshold limit and the *SI* at normal condition and at the instant of fault detection for SLG fault case. It is clear that, the suggested threshold succeeds to distinguish between normal and faulty conditions.

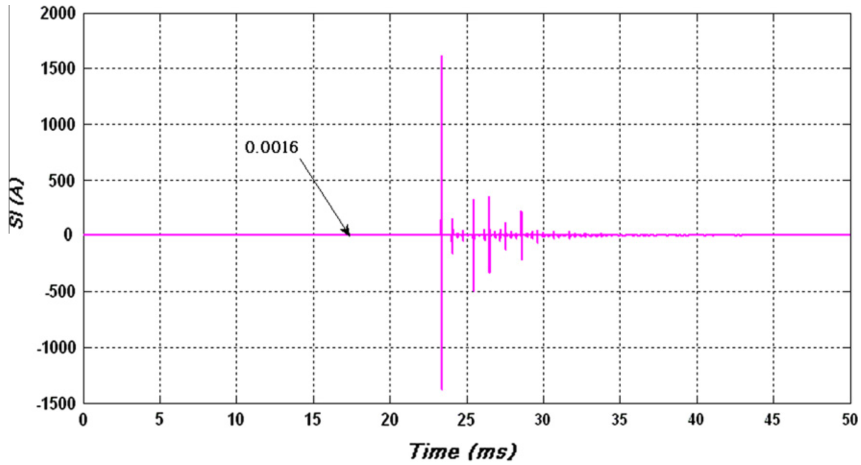

Figure 4 Pre and post fault condition SOD transform response.

Table 2 Sampling frequency and threshold limit.

Sample rate (kHz)	The threshold limit value	The *SI* value at normal operation (A)	*SI* value at the detection instant (A)
50	0.1	0.0047	465.1767
100	0.05	0.0016	144.2990
150	0.0333	0.0022	33.9162
200	0.025	0.0021	284.2883
250	0.02	0.0019	726.1434
300	0.0167	0.0018	382.7594
400	0.0125	0.0018	562.4999
500	0.01	0.0020	701.8373
600	0.0083	0.0019	174.4579

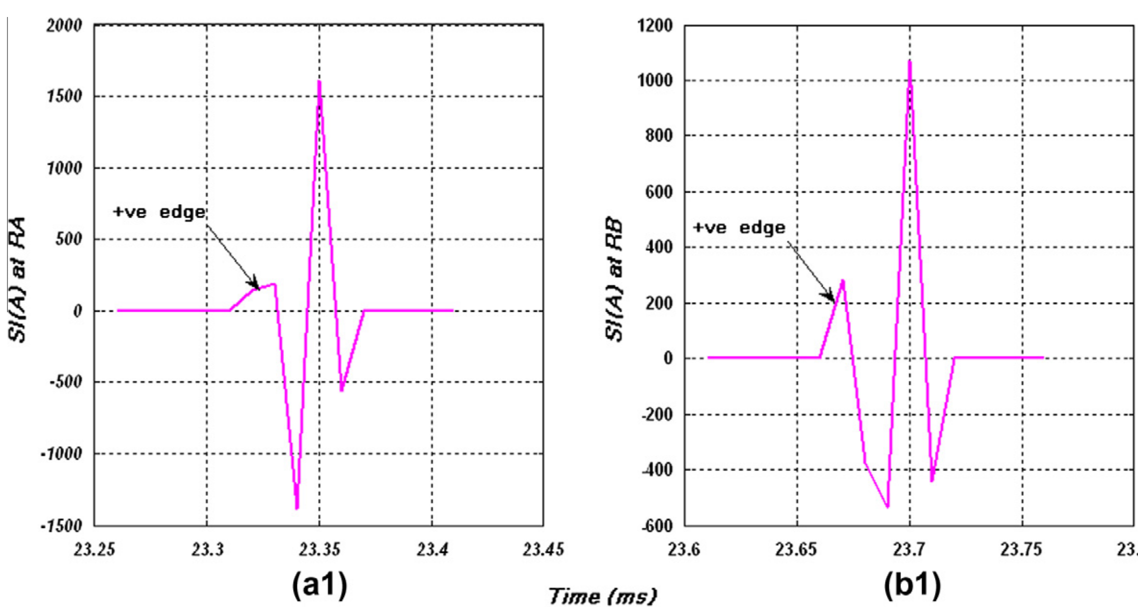

Figure 5 1st Edge polarities of the *SI* signals at the two relaying stations for phase a to ground internal fault.

As the absolute value of the *SI* signal exceeds the threshold limit, ρ, the starting **criterion records its** polarity and exchanges it between the relaying stations through the communication channels. It is worth to mention that, a confirmation of the exceeding of the threshold limit is done, sequentially for three samples, before transferring the polarities.

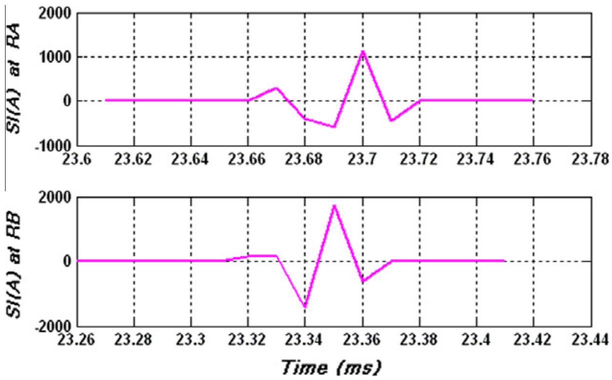

Figure 6 Relays response for F1, internal fault, at 23 ms inception time.

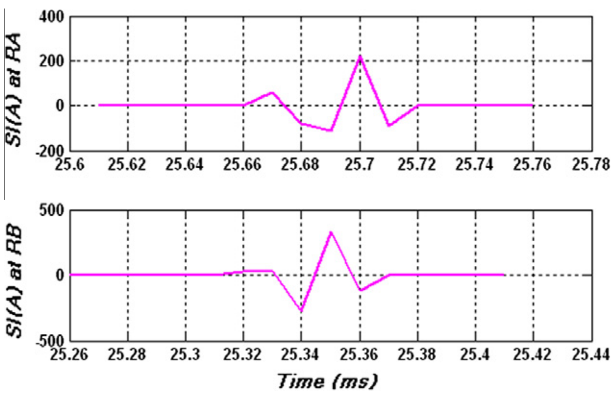

Figure 7 Relays response for F1, internal fault, at 25 ms inception time.

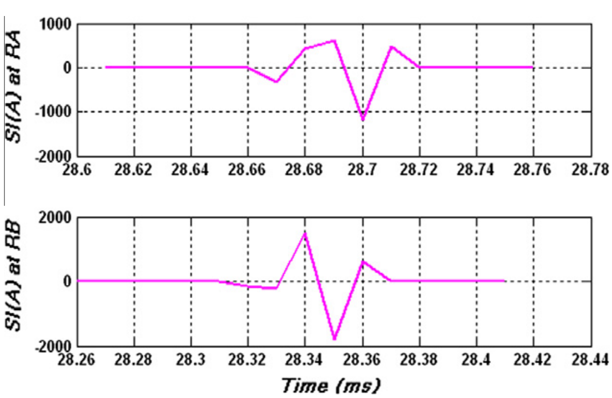

Figure 8 Relays response for F1, internal fault, at 28 ms inception time.

4.2. *The internal/external discriminator criterion*

By exchanging the recorded polarities between the relaying stations, the discriminator **criterion** compares these polarities at each relay location with respect to each other. The comparison is done by examining the similarity/dissimilarity. It is illustrated by Fig. 5 that; similar polarities indicate internal faults. The dissimilar polarities indicate external

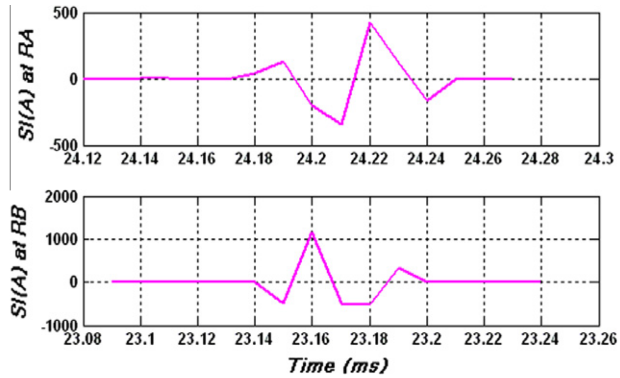

Figure 9 Relays response for F3, external fault, 50 km from bus B, at 23 ms inception time.

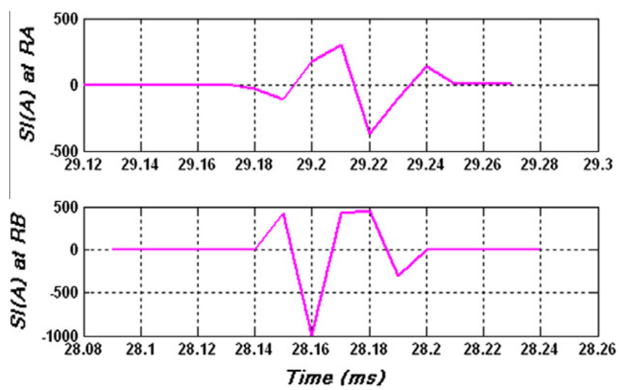

Figure 10 Relays response for F3, external fault, 50 km from bus B, at 28 ms inception time.

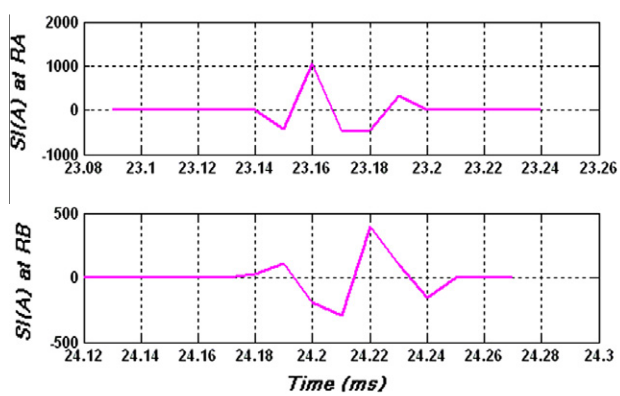

Figure 11 Relays response for F5, external fault, 50 km from bus A, at 23 ms inception time.

faults or load switching operation, according to current transformers direction shown by Fig. 1.

4.3. *Application on two sides fed transmission lines*

To apply the proposed protective concept on the two sides fed transmission lines, two relays, one at each end of the protected line, must be supported. Each relay of the two relays implements the two operating criteria, which are previously

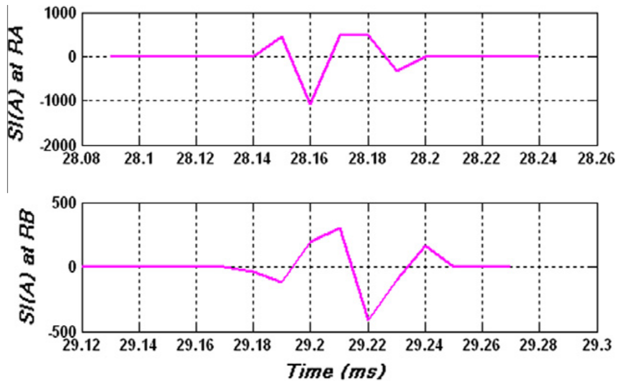

Figure 12 Relays response for F5, external fault, 50 km from bus A, at 28 ms inception time.

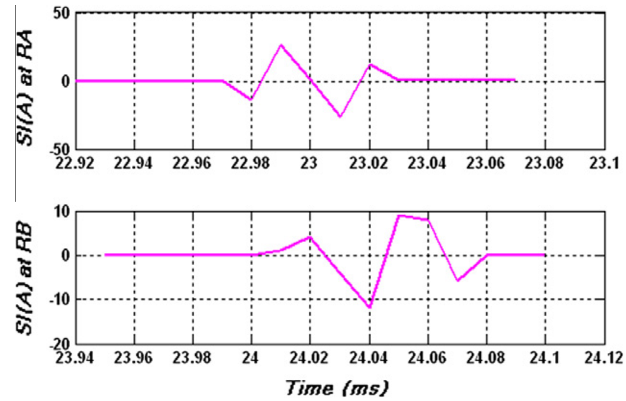

Figure 13 Relays response during load switching at bus A.

Table 3 Relays response for different fault inception times and different fault modes.

Fault mode	The *SI* values at the detection instant					
	23 ms		25 ms		28 ms	
	RA	RB	RA	RB	RA	RB
F1 internal	303.7381	149.3779	58.4259	28.7341	−318.6580	−156.7148
F3 external	36.1677	−484.6978	10.7194	−143.6609	−31.5422	422.7166
F5 external	−431.3650	31.5340	−86.0021	6.2865	447.4072	−32.7077

Table 4 Relays response for different power flow direction and different fault modes.

Fault mode	The *SI* values at the detection instant					
	Flow from A–B		Flow from B–A		No load	
	RA	RB	RA	RB	RA	RB
F1 internal	−905.4614	−887.1146	−904.8718	−886.5373	−916.9515	−898.3716
F2 external	−701.3637	1103	−83.2312	1115	−715.2521	1125
F4 external	1127	−701.9716	1113	−81.3460	1133	−705.7840

Table 5 Relays response for different fault location and different fault types.

The *SI* values at the detection instant						
Fault type	30 km from A		90 km from A		270 km from A	
	RA	RB	RA	RB	RA	RB
b-g	600.1224	14.2326	733.8840	959.0121	15.1408	612.8212
bc-g	1204	28.5419	1.5236e + 003	1991	34.4365	1393.8
Bc	1404	33.2850	1759.6	2299.4	38.8068	1570.7
Abc	397.6587	9.4308	572.9119	748.6595	16.8272	681.0734

mentioned. Using the convention of direction of current transformers shown by Fig. 1, similarity of the *SI* polarities indicates internal fault.

The proposed relaying concept response to several fault cases is examined. F1 represents the internal faults while F2, F3, F4 and F5 represent the external faults, see Fig. 1. The next presented Figs. will show the interested portion of the *SI* signals at the two relays, *RA* and *RB*. Figs. 6–8 show the proposed concept response for solid SLG-ag faults located internal the protected line, F1, 200 km from bus A. The fault inception time is studied at 23 ms, 25 ms and 28 ms respectively. Figs. 9 and 10 show the response for solid SLG-ag faults located external the protected line, F3, 50 km from bus B, occurred at 23 ms and 28 ms respectively, while Figs. 11 and 12 show the same for F5 faults, 50 km from bus A. Table 3 summarized the values of the *SI* signals at the detection instant at both line ends for different fault inception times and different fault modes, internal and external.

Figs. 6–8 indicate internal fault cases as the *SI* polarities at both ends are identical, so a tripping decision will be taken. Figs. 9–12 indicate external fault cases as the polarities of the *SI* signals at both the relaying stations have opposite

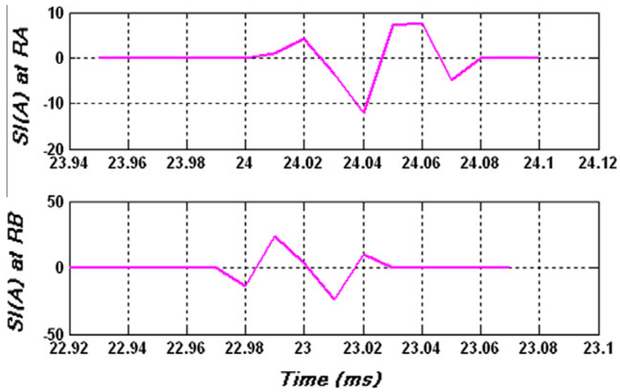

Figure 14 Relays response during load switching at bus B.

polarities. Although the threshold limit, ρ, is very small, 0.05, it presents high success to discriminate between normal and fault conditions. The variation of the fault inception time does not affect the two relays responses, the *SI* polarities still identical for internal faults and opposite for external faults. Table 3 show the same notifications.

4.3.1. Power flow effect

In this section, the effect of power flow on the protective transmission line is examined. Three power flow conditions include flow from A–B, B–A and no load are studied. Table 4 summarized the values of the *SI* signals, at the detection instant, at both line ends, for the above-mentioned three conditions, for internal and external fault cases.

Results show that, the *SI* signals give identical polarities for internal faults and give opposite polarities for external faults, which indicate that the power flow direction has no effect upon the *SI* signals polarities, even with no load, capacitive charging current.

4.3.2. Fault type effect

Fault type effect on the proposed SOD relaying concept is studied. Table 5 shows the values of the *SI* signals, at the detection instant, for various fault types, for both RA and RB.

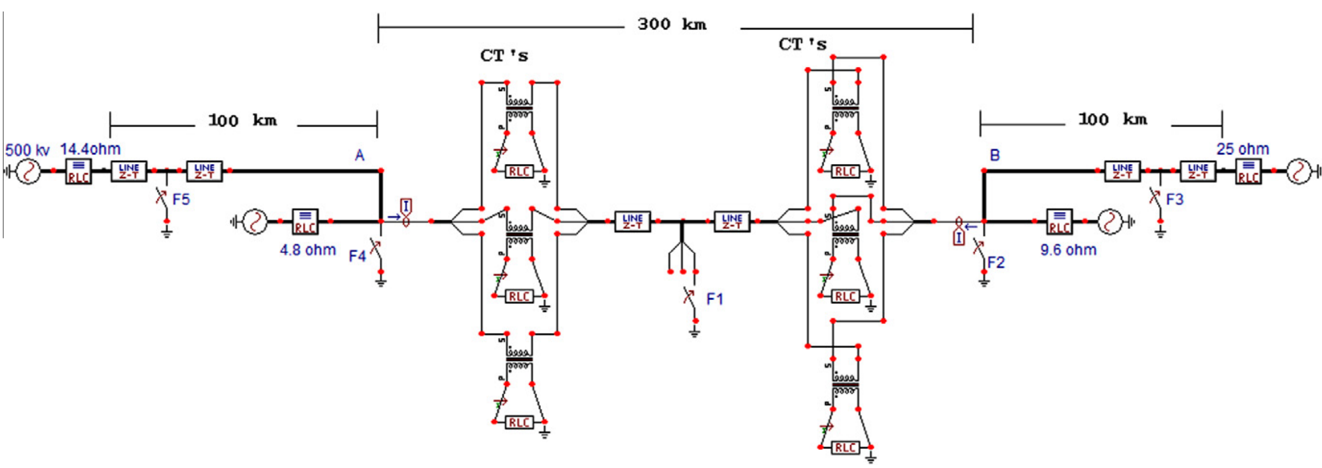

Figure 15 The studied configuration system including the CT model of the ATP program.

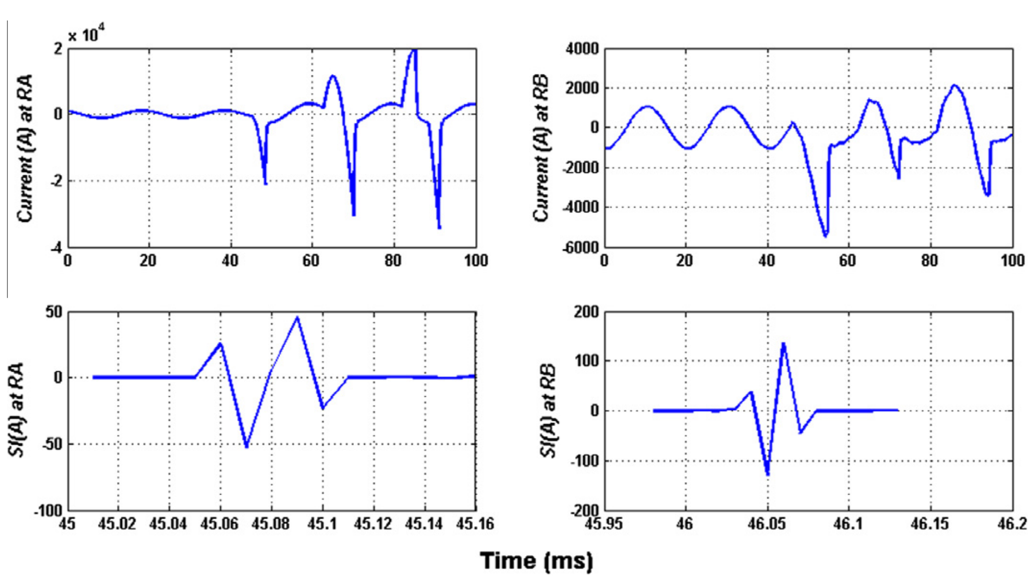

Figure 16 Relays response during CT saturation case for F1, internal fault, at 45 ms inception time.

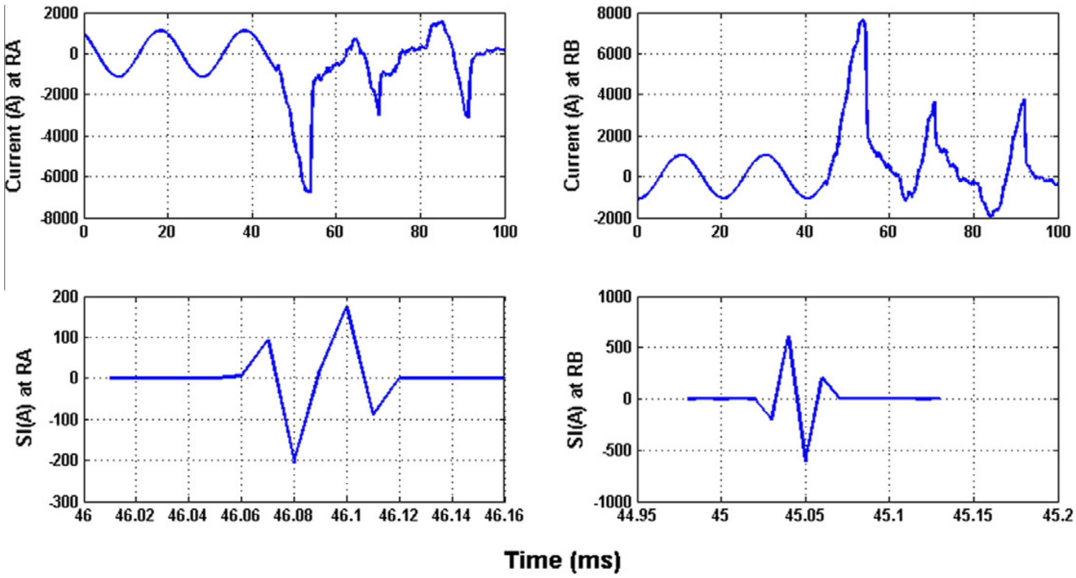

Figure 17 Relays response during CT saturation case for F2, external fault, at 45 ms inception time.

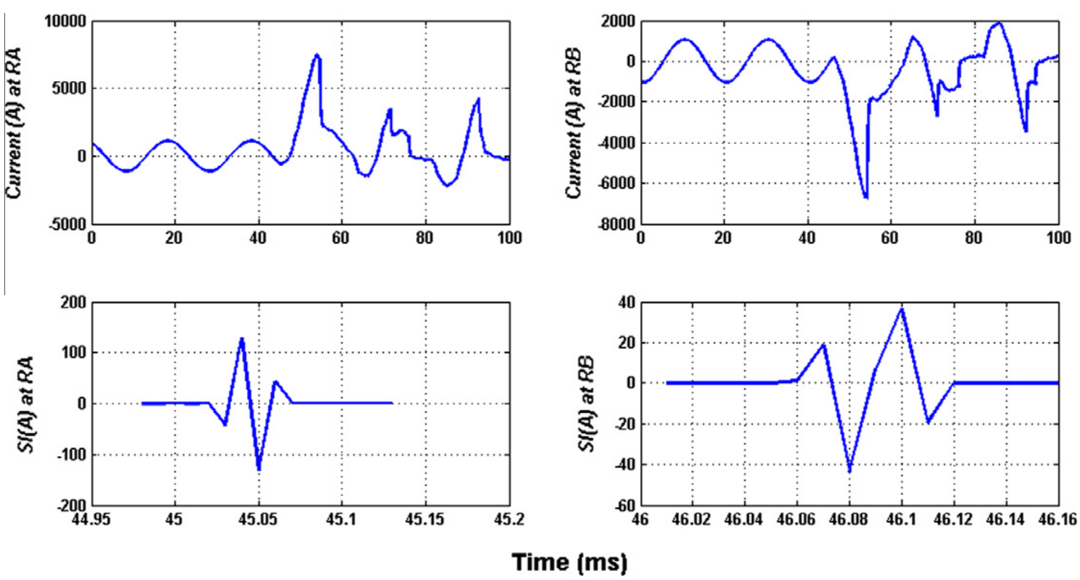

Figure 18 Relays response during CT saturation case for F4, external fault, at 45 ms inception time.

The *SI* values shown by Table 5 show that, the SOD relaying concept gives correct response to all fault types.

4.3.3. Load switching effect

At certain switching instant during load switching, the SI signals might exceed the threshold limit. Discrimination between the transient components initiated due to such reasons and those due to direct faults becomes very essential. Figs. 13 and 14 show the response for two load switching cases located at bus A and bus B respectively.

Results show that, although the *SI* signals exceed the threshold limit, the proposed unit protective concept does not classify these switching as internal faults because the *SI* signals have two opposite signs.

4.3.4. CT's saturation effect

This section shows the simulation results obtained from typical CT's, to show the proposed relaying concept response under CT saturation events. To simulate CT saturation events, CT model of the Alternative-Transients Program is used. Fig. 15 shows the studied configuration system including the CT model. Figs. 16–18 show internal fault case at F1, external fault case at F4 and external fault case at F2 respectively.

The results indicate that the technique is very effective in preventing false tripping during external fault conditions due to CT saturation. It is clear that the proposed concept is useful to assure proper operation of the protection for internal and external faults with CT saturation.

5. Conclusion

A novel transient unit protective relaying concept based on simple sequential overlapping derivative, SOD, is proposed. The SOD transform processes the positive sequence current signals. The unit protective relaying concept uses both polarity and magnitude of the *SI* signals provide a compact description of the power system disturbances. One of the benefits of this new concept lies in that calculations are simplified. This concept is capable of instantaneously identifying internal and (external faults and load switching). Also it has immunity against the influence of the large capacitance of the line, the saturation of the current transformers and the synchronization problems. At the same time it has high reliability and security. The detection time is nearly equal to the time required for the disturbance to travel from the fault point to the relay location. The performance of the proposed protective relaying concept is evaluated on the two-terminal transmission line.

Appendix A

The transmission-line parameters are as given below:

zero-sequence resistance, reactance and capacitance: $R_0 = 0.247\,\Omega/\text{km}$, $L_0 = 0.91\,\Omega/\text{km}$ and $C_0 = 2.94$ uMho/km respectively;

positive-sequence resistance, reactance and capacitance: $R_1 = 0.0217\,\Omega/\text{km}$, $L_1 = 0.302\,\Omega/\text{km}$ and $C_1 = 3.96$ uMho/km respectively;

source voltages: 500 kV.

source impedances are shown by Fig. 1.

Appendix B

The positive sequence quantity can be expressed as follows [16]:

$$3I_P(k) = I_A(k) - 2I_C(k) + I_B(k) + 1.7321(I_C(k-1) - I_B(k-1)) \quad (6)$$

$$I_1(k) = 3I_P(k) \quad (7)$$

where I_A, I_B and I_C are three phase power frequency voltages or currents, and I_P is positive sequence quantity. Eq. (6) requires only one sample delay to compute the positive sequence quantity, therefore significantly increase the speed of the computation.

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