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Correlation-based polarity-check algorithm for instrument transformers

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Abstract
A polarity identification is very important for operation of transformers, measurement and protection equipment, where it is useful in analyzing of transformer connections and operation as well as testing of protective systems. Moreover, it's essential in assessment of power systems performance during both normal and abnormal operation. Ensuring the correct polarity of the primary and secondary windings in voltage and current transformers is of paramount importance for various measurement and protection schemes in power networks. This paper proposes a digital polarity detector and tester using correlation coefficients and nine polarity indices calculated for instrument transformer signals. In order to test the performance of the proposed polarity tester algorithm, MATLAB code is imported to the LABVIEW model, and the numerical data obtained from the synchronous generator terminals via instrument transformers are interfaced with the computer through the Data Acquisition Card (DAC). The experimental system consists of a motor-generator set supplying a three-phase inductive load with instrument transformers connected to measure each phase voltage and current. The obtained results for various operating conditions and different types of abnormal conditions prove that the suggested algorithm is accurate, reliable and applicable to smart grids and substation automation systems. It can be considered as an integrated system incorporated with digital fault recorders, relays and meters.

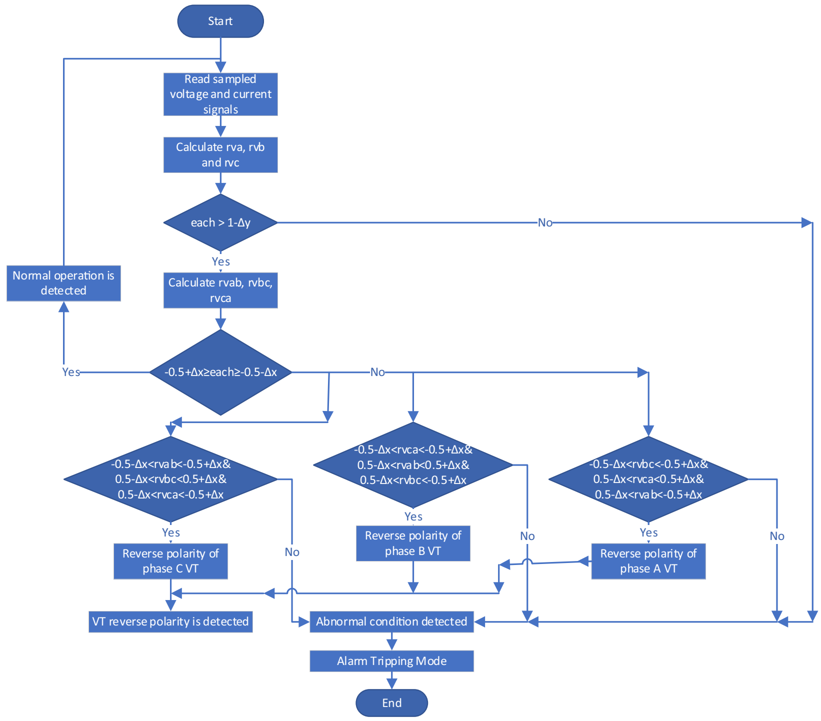
Keywords: Instrument transformers, Polarity tester, Correlation coefficient, Digital relays, Digital meters

Introduction
In reality, protective relays mal-operations still happen from time to time. The common reasons of mal-operations are: CT polarity error in design or construction, relay failure, CT saturation, incorrect settings of protective relay, lack of coordination of various relays of adjacent feeders, inrush current during energization or voltage recovery [1–5]. This paper will focus on the first type of mal-operations to detect CT polarity error [6]. The current transformer polarity tester determines the direction of the secondary current in relation to the primary current. Wrong connection of the current transformers can cause false operation of the protective relays as well as power and energy meters [7, 8]. Checking the polarity of voltage or current transformers is extremely important, since it is vital to ensure that the instrument transformers are connected with the correct polarity. Moreover, Interconnection of electrical devices always require correct polarity to be

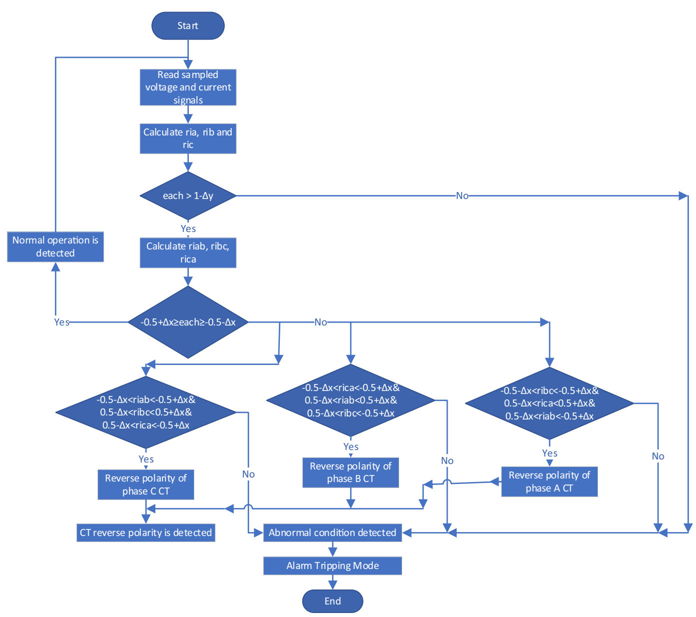
maintained, also it is essential for the operation of many electric motors, tap changers of power transformers, and other devices [9]. In general, it is required to ensure proper functions of power systems [10]. The polarity marks for transformers are well established by standards that apply to all types of transformers. Power and instrument transformers are subtractive, whereas some distribution transformers are additive [11, 12]. The polarity detection and testing is essential for correct wiring and for discriminating between forward and reverse powers, moreover, it is useful for differentiating between import and export energies. In addition, it is used to modify the voltage magnitude by power transformer tap changer for implementing synchronization process [13, 14]. Various techniques have been developed for polarity detection and testing of instrument transformers [15, 16]. These techniques make decision to switch the terminals of voltage or current transformer in the case of polarity reverse detection. Incorrect connection of the instrument transformers can cause false operation of various protection schemes such as differential overcurrent [17], directional [18], reverse power [19], synchro-check [20, 21], Out-of-step protection [22, 23], loss of field [24], and phasor measurement unit [25]. In this article, a digital polarity detector and tester using numerical technique based on correlation coefficients, calculated for voltage and current signals measured by instrument transformers, is proposed. The suggested algorithm requires both auto and cross-correlation coefficients calculated for measured phase voltage and current signals [20, 26]. In this method, the auto-correlation coefficients estimated for each phase voltage and current signals are computed to affirm the normal operation condition; and the cross-correlation coefficients evaluated for each two phase signals are estimated to assure the correct polarity condition for instrument transformers. The instrument transformer polarity test is performed automatically in the presented algorithm with fast response time, high precision and reliability. Thus, this algorithm is considered as an additional function can be impeded in digital relays, meters and fault recorders.

Proposed digital polarity tester

In this paper, a digital polarity tester is proposed to detect the correct and reverse polarity conditions for voltage and/or current measured via voltage and current transformers, respectively, located at three-phase synchronous generator terminals. In the proposed algorithm, the polarity is determined by calculating auto/cross-correlation coefficients for voltage and current signals of the VT and/or CT separately for each phase. Application of the numerical technique based on correlation analysis makes the scheme fast in detecting polarity abnormal condition, accurately assessing the degree of unbalance and clearly discriminating it from normal condition by utilizing the data of voltage and current signals obtained at synchronous generator terminals. The process of polarity condition detection is performed sequentially with a maximum execution time of one cycle of the fundamental component. Description of the design procedure and performance analysis of the proposed polarity tester are presented in this paper. This is experimentally demonstrated on a motor-generator set exposed to different types of operating conditions for various instrument transformers. The following section describes the mathematicaformulas and the flow charts, shown in Fig. 1 (a-c), which explains how the algorithm works.

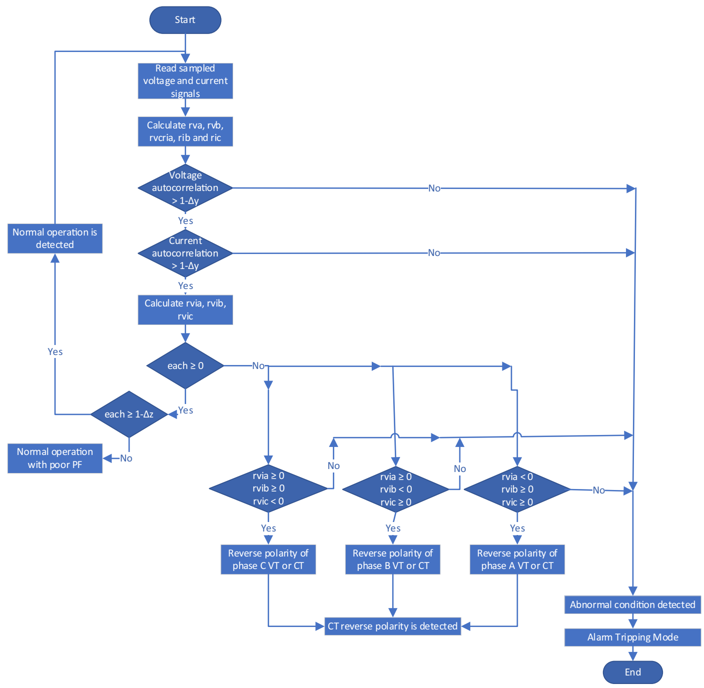


(a) Flow chart of the proposed algorithm based on correlation concept for rdetection of VT everse polarity condition.

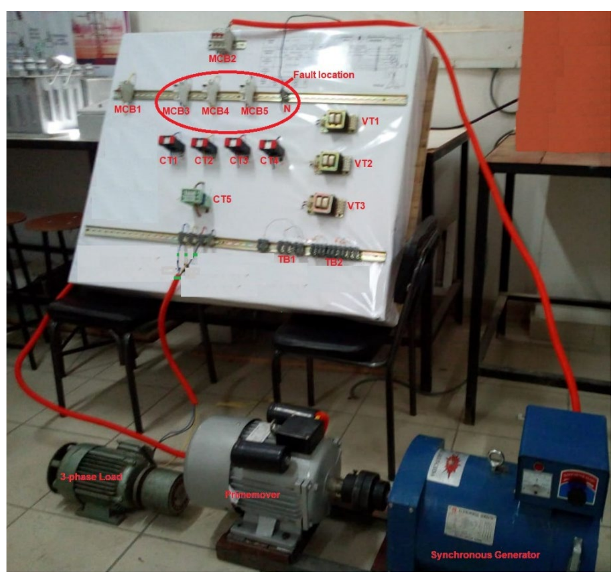


(b) Flow chart of the proposed algorithm based on correlation concept for detection of CT reverse polarity condition.

Fig. 1 Flow chart of the proposed algorithm based on correlation concept for detection of **a** VT reverse polarity condition. **b** CT reverse polarity condition. **c** VT or CT reverse polarity condition. **d** The experimental system under test



(c) Flow chart of the proposed algorithm based on correlation concept for detection of VT or CT reverse polarity condition.



(d) The experimental system under test.

Fig. 1 continued

Cross-correlation coefficient estimation

The cross-correlation coefficient, r_{vis} is computed between a data window with a certain number of samples (N) of an electrical signal ($v_{ss}(n)$) and another corresponding data window with the same number of samples of another electrical signal ($i_{ss}(n)$).

To estimate the cross-correlation coefficient (r_{vis}) between the two digitized electrical signals ($v_{ss}(n)$ and $i_{ss}(n)$), Eq. (1) can be applied [20, 26–28]:

$$r_{xy}=\frac{\left[\sum_{n=1}^{N}x(n)y(n)-\frac{1}{N}x(n)\sum_{n=1}^{N}y(n)\right]}{\left[\sqrt{\sum_{n=1}^{N}(x(n))^2-\frac{1}{N}\left(\sum_{n=1}^{N}x(n)\right)^2}\right]\times\left[\sqrt{\sum_{n=1}^{N}(y(n))^2-\frac{1}{N}\left(\sum_{n=1}^{N}y(n)\right)^2}\right]} \tag{1}$$

where r_{xy}: cross-correlation coefficient calculated between each two corresponding windows for the two electrical signals ($x(n)$ *and* $y(n)$).

Auto-correlation coefficients estimation

The auto-correlation coefficients, r_x, r_y are estimated between two successive data windows, shifted from each other by one cycle with a certain number of samples (N) for electrical power signals ($x(n)$, $y(n)$) respectively measured for '*S*' phase.

To evaluate the two auto-correlation coefficients (r_x and r_y), Eqs. (2–3) can be used [20, 26–28]:

$$r_x=\frac{\left[\sum_{n=1}^{N}x(n)x(n-N_s)-\frac{1}{N}x(n)\sum_{n=1}^{N}x(n-N_s)\right]}{\left[\sqrt{\sum_{n=1}^{N}(x(n))^2-\frac{1}{N}\left(\sum_{n=1}^{N}x(n)\right)^2}\right]\times\left[\sqrt{\sum_{n=1}^{N}(x(n-N_s))^2-\frac{1}{N}\left(\sum_{n=1}^{N}x(n-N_s)\right)^2}\right]} \tag{2}$$

$$r_y=\frac{\left[\sum_{n=1}^{N}y(n)y(n-N_s)-\frac{1}{N}y(n)\sum_{n=1}^{N}y(n-N_s)\right]}{\left[\sqrt{\sum_{n=1}^{N}(y(n))^2-\frac{1}{N}\left(\sum_{n=1}^{N}y(n)\right)^2}\right]\times\left[\sqrt{\sum_{n=1}^{N}\left(y(n-N_s)\right)^2-\frac{1}{N}\left(\sum_{n=1}^{N}y(n-N_s)\right)^2}\right]} \tag{3}$$

where $x(n\text{-}N_s)$, $y(n\text{-}N_s)$: The pre-cycle sampled electrical signal at instant $n-N_s$ measured for '*S*' phase.

The correlation setting deviations (Δx, Δy and Δz) should lie in the range from 0 to 0.25 to avoid the mal-operation of the protection scheme due to effects of acceptable overload currents, decent harmonics and temporary (transient) faults [26]. These settings are carefully selected according to the prevailed conditions and the acceptable unbalance level in power system. In this study, the selected values of correlation setting deviations (Δx, Δy and Δz) are 0.25, 0.1 and 0.1, respectively.

Polarity indices estimation

The following mathematical equations exhibit the cross-correlation coefficients (calculated for three phase voltage and current signals), which are used for calculating the polarity indices:

$$rv_{ab}=\frac{\left[\sum_{n=1}^{N}v_a(n)v_b(n)-\frac{1}{N}v_a(n)\sum_{n=1}^{N}v_b(n)\right]}{\left[\sqrt{\sum_{n=1}^{N}(v_a(n))^2-\frac{1}{N}\left(\sum_{n=1}^{N}v_a(n)\right)^2}\right]\times\left[\sqrt{\sum_{n=1}^{N}(v_b(n))^2-\frac{1}{N}\left(\sum_{n=1}^{N}v_b(n)\right)^2}\right]} \tag{4}$$

$$rv_{bc} = \frac{\left[\sum_{n=1}^{N} v_b(n)v_c(n) - \frac{1}{N}v_b(n)\sum_{n=1}^{N} v_c(n)\right]}{\left[\sqrt{\sum_{n=1}^{N}(v_b(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} v_b(n)\right)^2}\right] \times \left[\sqrt{\sum_{n=1}^{N}(v_c(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} v_c(n)\right)^2}\right]} \tag{5}$$

$$rv_{ca} = \frac{\left[\sum_{n=1}^{N} v_c(n)v_a(n) - \frac{1}{N}v_c(n)\sum_{n=1}^{N} v_a(n)\right]}{\left[\sqrt{\sum_{n=1}^{N}(v_c(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} v_c(n)\right)^2}\right] \times \left[\sqrt{\sum_{n=1}^{N}(v_a(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} v_a(n)\right)^2}\right]} \tag{6}$$

$$ri_{ab} = \frac{\left[\sum_{n=1}^{N} i_a(n)i_b(n) - \frac{1}{N}i_a(n)\sum_{n=1}^{N} i_b(n)\right]}{\left[\sqrt{\sum_{n=1}^{N}(i_a(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} i_a(n)\right)^2}\right] \times \left[\sqrt{\sum_{n=1}^{N}(i_b(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} i_b(n)\right)^2}\right]} \tag{7}$$

$$ri_{bc} = \frac{\left[\sum_{n=1}^{N} i_b(n)i_c(n) - \frac{1}{N}i_b(n)\sum_{n=1}^{N} i_c(n)\right]}{\left[\sqrt{\sum_{n=1}^{N}(i_b(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} i_b(n)\right)^2}\right] \times \left[\sqrt{\sum_{n=1}^{N}(i_c(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} i_c(n)\right)^2}\right]} \tag{8}$$

$$ri_{ca} = \frac{\left[\sum_{n=1}^{N} i_c(n)i_a(n) - \frac{1}{N}i_c(n)\sum_{n=1}^{N} i_a(n)\right]}{\left[\sqrt{\sum_{n=1}^{N}(i_c(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} i_c(n)\right)^2}\right] \times \left[\sqrt{\sum_{n=1}^{N}(i_a(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} i_a(n)\right)^2}\right]} \tag{9}$$

$$rvi_{a} = \frac{\left[\sum_{n=1}^{N} v_a(n)i_a(n) - \frac{1}{N}v_a(n)\sum_{n=1}^{N} i_a(n)\right]}{\left[\sqrt{\sum_{n=1}^{N}(v_a(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} v_a(n)\right)^2}\right] \times \left[\sqrt{\sum_{n=1}^{N}(i_a(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} i_a(n)\right)^2}\right]} \tag{10}$$

$$rvi_{b} = \frac{\left[\sum_{n=1}^{N} v_b(n)i_b(n) - \frac{1}{N}v_b(n)\sum_{n=1}^{N} i_b(n)\right]}{\left[\sqrt{\sum_{n=1}^{N}(v_b(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} v_b(n)\right)^2}\right] \times \left[\sqrt{\sum_{n=1}^{N}(i_b(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} i_b(n)\right)^2}\right]} \tag{11}$$

$$rvi_{c} = \frac{\left[\sum_{n=1}^{N} v_c(n)i_c(n) - \frac{1}{N}v_c(n)\sum_{n=1}^{N} i_c(n)\right]}{\left[\sqrt{\sum_{n=1}^{N}(v_c(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} v_c(n)\right)^2}\right] \times \left[\sqrt{\sum_{n=1}^{N}(i_c(n))^2 - \frac{1}{N}\left(\sum_{n=1}^{N} i_c(n)\right)^2}\right]} \tag{12}$$

This section presents the novel mathematical formulas for identifying polarity indices (i.e. directionality factors) for three phase voltage and current transformers, which are derived from the cross-correlation coefficients estimated for three phase voltage and current signals. Therefore, the developed polarity indices are considered the main contribution in this article.

$$Fv_a = \frac{rv_{ab} \times rv_{ca}}{|rv_{ab} \times rv_{ca}|} \tag{13}$$

$$Fv_b = \frac{rv_{ab} \times rv_{bc}}{|rv_{ab} \times rv_{bc}|} \tag{14}$$

$$Fv_c = \frac{rv_{ca} \times rv_{bc}}{|rv_{ca} \times rv_{bc}|} \tag{15}$$

Table 1 offers the polarity indices for three phase voltage transformers, Table 2 shows the polarity indices for three phase current transformers, and Table 3 presents the polarity index for each phase voltage and current transformers. These indices confirm the

Table 1 Polarity indices for three phase voltage transformers

Factor type	Status of VTs polarities			
	Normal VTs polarities and normal operating condition	**Reverse polarity of 'A' phase *VT***	**Reverse polarity of 'B' phase *VT***	**Reverse polarity of 'C' phase *VT***
rv_{ab}	− 0.5	+ 0.5	+ 0.5	− 0.5
rv_{bc}	− 0.5	− 0.5	+ 0.5	+ 0.5
rv_{ca}	− 0.5	+ 0.5	− 0.5	+ 0.5
Fv_a	+ 1	+ 1	− 1	− 1
Fv_b	+ 1	− 1	+ 1	− 1
Fv_c	+ 1	− 1	− 1	+ 1

Table 2 Polarity indices for three phase current transformers

Factor type	Status of CT polarities			
	Normal CTs polarities and normal operating condition	**Reverse polarity of 'A' phase *CT***	**Reverse polarity of 'B' phase *CT***	**Reverse polarity of 'C' phase *CT***
ri_{ab}	− 0.5	+ 0.5	+ 0.5	− 0.5
ri_{bc}	− 0.5	− 0.5	+ 0.5	+ 0.5
ri_{ca}	− 0.5	+ 0.5	− 0.5	+ 0.5
Fi_a	+ 1	+ 1	− 1	− 1
Fi_b	+ 1	− 1	+ 1	− 1
Fi_c	+ 1	− 1	− 1	+ 1

Table 3 Polarity indices for three single phase voltage and current transformers

Factor type	Status of VT or CT polarity			
	Normal VTs and CTs polarity and normal operating condition	**Reverse polarity of 'A' phase VT or CT**	**Reverse polarity of 'B' phase VT or CT**	**Reverse polarity of 'C' phase VT or CT**
rvi_a	$+1 \geq rvi_a > 0$	$rvi_a < 0$	$+1 \geq rvi_a > 0$	$+1 \geq rvi_a > 0$
rvi_b	$+1 \geq rvi_b > 0$	$+1 \geq rvi_b > 0$	$rvi_b < 0$	$+1 \geq rvi_b > 0$
rvi_c	$+1 \geq rvi_c > 0$	$+1 \geq rvi_c > 0$	$+1 \geq rvi_c > 0$	$rvi_c < 0$
Fvi_a	+ 1	− 1	+ 1	+ 1
Fvi_b	+ 1	+ 1	− 1	+ 1
Fvi_c	+ 1	+ 1	+ 1	− 1

correct and reverse polarity of each phase VT or CT according to the data listed in the three tables below.

$$Fi_a = \frac{ri_{ab} \times ri_{ca}}{|ri_{ab} \times ri_{ca}|} \tag{16}$$

$$Fi_b = \frac{ri_{ab} \times ri_{bc}}{|ri_{ab} \times ri_{bc}|} \tag{17}$$

$$Fi_c = \frac{ri_{ca} \times ri_{bc}}{|ri_{ca} \times ri_{bc}|} \tag{18}$$

$$Fvi_a = \frac{rvi_a}{|rvi_a|} \tag{19}$$

$$Fvi_b = \frac{rvi_b}{|rvi_b|} \tag{20}$$

$$Fvi_c = \frac{rvi_c}{|rvi_c|} \tag{21}$$

where Fv_a, Fv_b and Fv_c: The polarity indices (i.e. directionality factors) for three phase voltage transformers, Fi_a, Fi_b and Fi_c: The polarity indices for three phase current transformers, Fvi_a, Fvi_b and Fvi_c: The polarity indices for three single phase voltage and current transformers.

Advantages of the polarity indices are as follows:

(I) No need to select the pre-setting values of correlation coefficients,

(II) The polarity tester algorithm uses only two values of + 1 and -1 for determining the polarities of instrument transformers are correct or not, then the appropriate decision is taken utilizing relays and meters in the cases of correct and reverse polarities of three phase VTs and CTs, and

(III) It can be used as integrated algorithm for digital polarity tester, power factor meter, fault recorder and protection relay for generation, transmission, distribution and sub-distribution power systems.

Power system model under test

In order to verify the performance of the proposed protection scheme, a practical system model is built [29], then three phase VTs and CTs signals are analyzed in LABVIEW environment. The parameters of the power system under test are given in Table 4 and its components are shown in Fig. 1d. Three voltage transformers (VT_1, VT_2 and VT_3) and three current transformers (CT_1, CT_2 and CT_3) are constructed at synchronous generator load side. CT_4 is considered as a neutral current transformer for neutral current signal, and CT_5 represents a residual current transformer for three-phase current signals. The system model parameters are given in Table 4.

Table 4 The parameters data of the experimental power system model under test

Power system model parameter	Data
Three phase synchronous generator (*Power supply*)	
Type	STC-7.5 (Star connection)
Rated power	7.5 kW
Rated speed	1500 rpm
Rated line voltage	380 V
Rated line current	14.2 A
Rated frequency	50 Hz
Number of pair poles	2
Excitation voltage	100 V
Excitation current	4 A
Neutral grounding impedance (Rn)	Isolated
Single phase induction motor (*Prime mover*)	
Type	YC132SA – 4
Rated power	5 Hp (3.71 kW)
Nominal phase voltage	220 V
Rated current	23 A
Nominal frequency	50 Hz
Nominal power factor	0.80
Three phase induction motor (*Load*)	
Rated power	1.85 kW (Star connection)
Rated line voltage	400 V
Rated line current	2.7 A
Nominal frequency	50 Hz
Rated speed	1400 rpm
Current transformer (*CT*)	
CTR	200/5
Rated burden	5 VA
CT burden	1 Ω
Voltage Transformer (*VT*)	
VTR	220 V/ 5 V
Rated burden	5 VA
Miniature Circuit Breaker (*MCB1*)	
Phase type	Single phase
Rated current	63 A
Rated voltage	380 V
Miniature Circuit Breaker (*MCB2*)	
Phase type	Three phase
Rated voltage	380 V
Miniature Circuit Breakers (*MCB3 MCB4 and MCB5*)	
Phase type	Single phase
Rated current	20 A
Rated voltage	380 V

The analog voltage signals are fed to the A/D converter of the Data Acquisition Card (National Instruments USB-6008/6009) and transformed to digital signals through Sample- and Hold-circuits with a sampling frequency of 2.5 kHz, namely, a sampling rate of 0.4 ms for each measuring process.

Extensive case studies of abnormal conditions are examined by application of different types of series and shunt faults on the synchronous generator terminals.

Digital relay (data acquisition card (DAC) and PC)

The National Instruments USB-6008/6009 is data acquisition device which provides connection to eight analog input (AI) channels, two analog output (AO) channels, 12 digital input/output (DIO) channels, and a 32-bit counter with a Full-Speed USB interface. It is characterized by 14-bit input resolution, 8 input channels single ended or 4 input channels differential and a maximum sampling rate of 48 kHz. The DAC is adjusted to operate in differential mode. In this study, each phase voltage or current signal are used with a sampling frequency of 2.5 kHz for each input channel. PC is used to virtually simulate the intelligent digital relay.

Practical results analysis

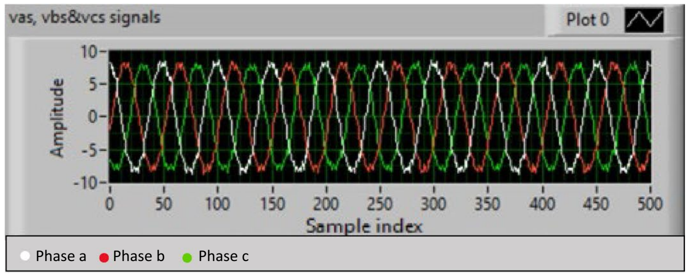
The DAC and LABVIEW software package are used for testing the proposed algorithm for detecting the instrument transformers polarities in the practical power system model. DAC is used to obtain the numerical data of voltage and current signals, measured at the synchronous generator output under different operating conditions for various voltage and current transformers. The proposed algorithm is implemented in MATLAB script of LABVIEW program for evaluating the scheme reliability after feeding the data from the experimental system via DAC. The total time of display is 0.2 Sec (i.e. the total number of samples = 500 samples).

Case study 1: correct polarity for three phase voltage transformers

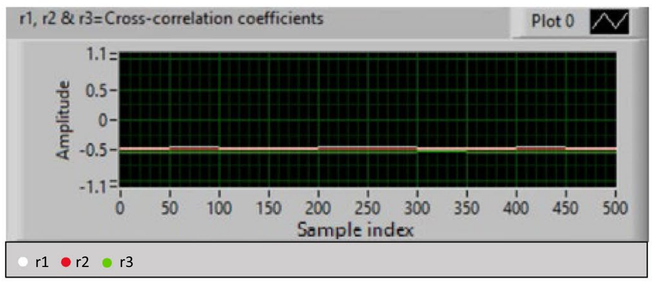
The practical results for case study 1 are shown in Fig. 2a–d. Figure 2a presents three phase secondary voltage signals at generator load terminals. It is obvious that the signals are intentionally injected without filtering in order to prove that the proposed technique with a correlated data window acts as a digital filter. Figure 2b plots the three cross-correlation coefficient values (r_1, r_2 and r_3) calculated between each two phase voltages (v_{as}, v_{bs}), (v_{bs}, v_{cs}), (v_{cs}, v_{as}), respectively. Their values are close to −0.5 during the displayed time (0.2 s). Figure 2c reveals the auto-correlation coefficient values (rv_a, rv_b and rv_c) evaluated for each phase secondary voltage signal. Their values are approximately 1, which is an indication of normal operating condition. Figure 2d shows the alarm signal in case of correct polarity for three phase voltage transformers, it's value is zero which indicates that the system condition has neither fault nor reversed polarity.

Case study 2: reverse polarity for 'A' phase VT_1

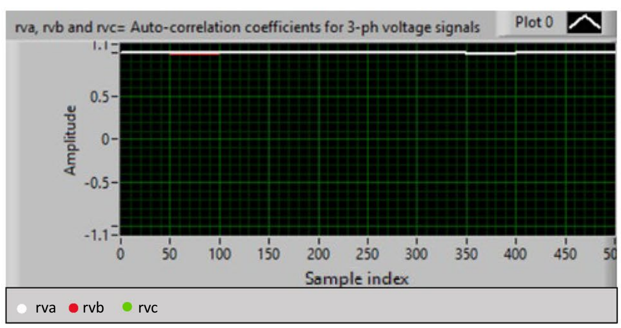
The practical results for case study 2 are shown in Fig. 3a–d. Figure 3a presents three phase secondary voltage signals at generator load terminals with reversed polarity of 'A' phase (VT_1). Figure 3b plots the three cross correlation coefficient values (r_1, r_2 and r_3) calculated between each two phase voltages (v_{as}, v_{bs}), (v_{bs}, v_{cs}), (v_{cs}, v_{as}) respectively. It is evident clear that r_2 is equal to −0.5 whereas r_1 and r_3 values are close to + 0.5, this confirms that the wire connection of VT_1 is reversed. Figure 3c shows the auto-correlation coefficient values (rv_a, rv_b and rv_c) evaluated for each phase secondary voltage signal. Their values are approximately 1, which is an indication of no-fault condition. The



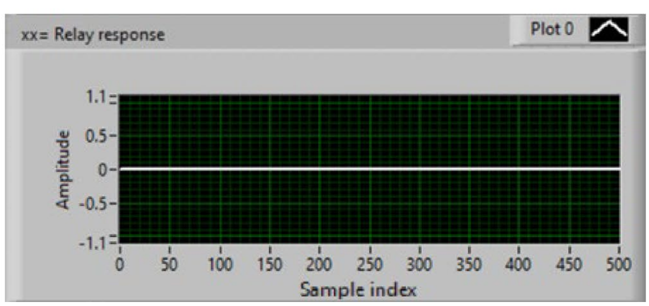
(a) Three phase secondary voltage signals at SG load terminals.



(b) The three cross-correlation coefficients (r_1, r_2, and r_3).

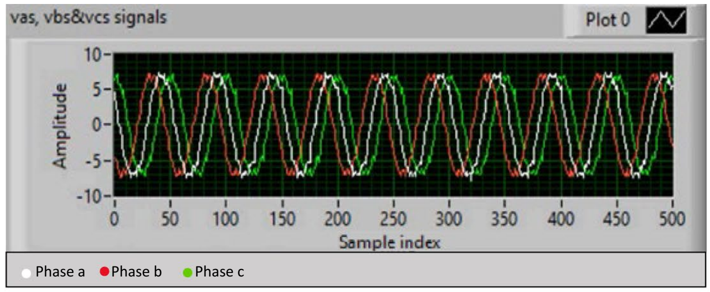


(c) The auto-correlation coefficients (rv_a, rv_b and rv_c) for three phase secondary voltage signals

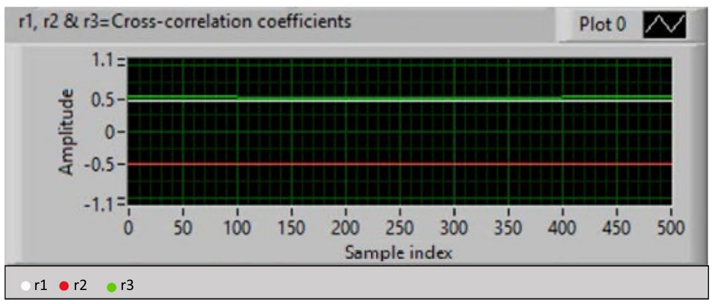


(d) Alarm signal in case of correct polarity for three phase voltage transformers.

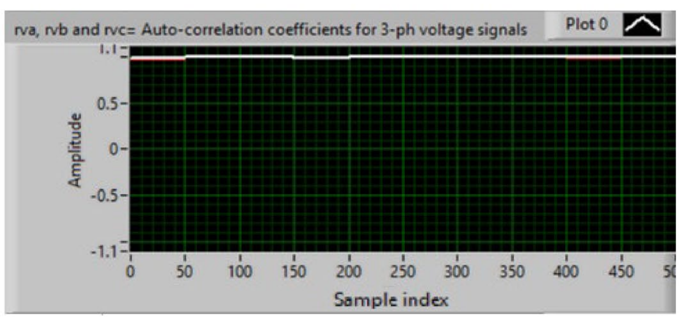
Fig. 2 **a** Three phase secondary voltage signals at SG load terminals. **b** The three cross-correlation coefficients (r_1, r_2, and r_3). **c** The auto-correlation coefficients (rv_a, rv_b and rv_c) for three phase secondary voltage signals. **d** Alarm signal in case of correct polarity for three phase voltage transformers. **a**–**d** The practical results for case study 1



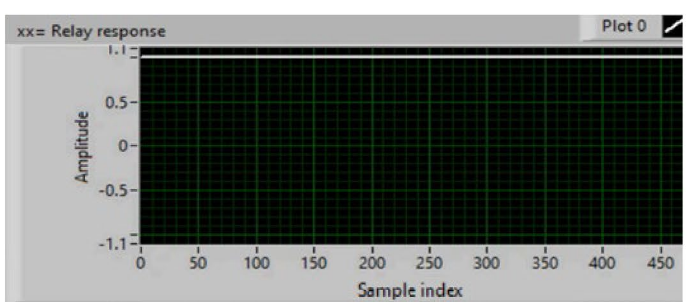
(a) Three phase secondary voltage signals at SG load terminals.



(b) The three cross-correlation coefficients (r_1, r_2, and r_3).



(c) The auto-correlation coefficients (rv_a, rv_b and rv_c) for three phase secondary voltage signals



(d) Alarm signal in case of reverse polarity for 'A' phase VT_1.

Fig. 3 **a** Three phase secondary voltage signals at SG load terminals. **b** The three cross-correlation coefficients (r_1, r_2, and r_3). **c** The auto-correlation coefficients (rv_a, rv_b and rv_c) for three phase secondary voltage signals. **d** Alarm signal in case of reverse polarity for 'A' phase VT_1. **a**–**d** The practical results for case study 2 previous discussion shows that both auto-correlation coefficients and cross-correlation coefficients are necessary to assure the normal operation condition with or without polarity reverse of one or two of voltage transformer(s). Figure 3d shows the alarm signal in case of correct polarity for three phase voltage transformers, it's value is 1 which affirms that the system condition has an abnormal condition (reversed polarity).

Case study 3: correct polarity for three phase current transformers

The practical results for case study 3 are shown in Fig. 4a–d. Figure 4a presents three phase secondary current signals at generator load terminals. Figure 4b plots the three cross-correlation coefficient values (r_1, r_2 and r_3) calculated between each two phase currents ($i_{as,}$ i_{bs}), ($i_{bs,}$ i_{cs}), ($i_{cs,}$ i_{as}) respectively. Their values are close to -0.5 during the displayed time (0.2 s). Figure 4c reveals the auto-correlation coefficient values (ri_a, ri_b and ri_c) evaluated for each phase secondary current signal. Their values are approximately 1, which is an indication of normal operating condition. Figure 4d shows the alarm signal in case of correct polarity for three phase current transformers, it's value is zero which indicates that the system condition has neither fault nor reversed polarity.

Case study 4: reverse polarity for 'C' phase CT_3

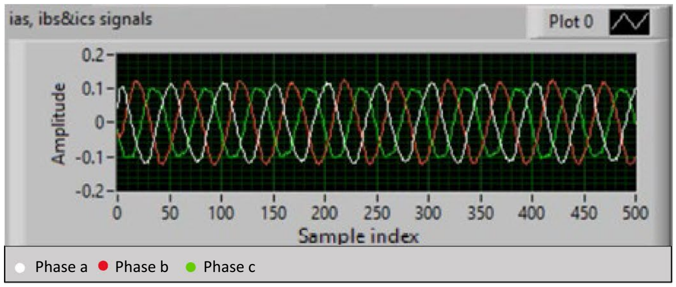
Figure 5a presents three phase secondary current signals at generator load terminals with reversed polarity of 'C' phase (CT_3). Figure 5b plots the three cross-correlation coefficient values (r_1, r_2 and r_3) calculated between each two phase currents ($i_{as,}$ i_{bs}), ($i_{bs,}$ i_{cs}), ($i_{cs,}$ i_{as}) respectively. It is clear that r_1 is close to -0.5 whereas r_2 and r_3 values are close to $+0.5$, this confirms that the wire connection of CT_3 is reversed. Figure 5c shows the auto-correlation coefficient values (ri_a, ri_b and ri_c) evaluated for each phase secondary current signal. Their values are approximately 1, which is an indication of healthy condition. Figure 5d shows the relay response with value $+1$ as a result of reversed polarity of CT_3.

Case study 5: correct polarity for 'A' phase VT_1 and CT_1

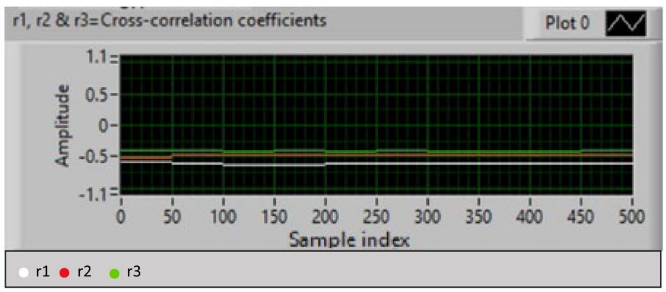
Case study 5 considers only phase 'A', where its voltage and current signals are shown in Fig. 6a and Fig. 6b, respectively. Figure 6c shows the cross-correlation coefficient (rvi_a) calculated between the phase voltage and current signals of 'A' phase which has a value of $+0.25$ depending on the phase angle between the two signals (i.e. power factor angle). The alarm signal in Fig. 6d has a value of zero as an indication of operating condition with normal power factor. The auto-correlation coefficients (rv_a and ri_a) of both voltage and current signals of phase 'A' are shown in Fig. 7 with a value of $+1$ which confirms no fault condition in the power system.

Case study 6: reverse polarity for 'A' phase VT_1

In case study 6, the polarity of voltage transformer VT_1 of '*A*' phase is intentionally reversed to test the polarity tester response. The voltage and current signals of '*A*' phase are shown in Fig. 8a, b, respectively. It is obvious from Fig. 8c that the cross-correlation coefficient (rvi_a) between the secondary voltage and current signals of '*A*' phase is reversed to have a value of -0.25 due to the reversal of VT_1 polarity. The alarm signal turns ON as shown in Fig. 8d, while the auto-correlation coefficients (rv_a and ri_a) for

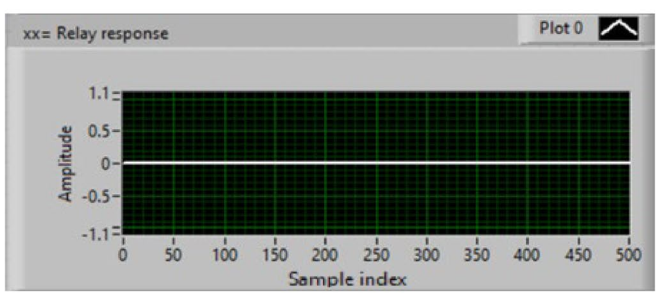


(a) Three phase secondary current signals at SG load terminals.



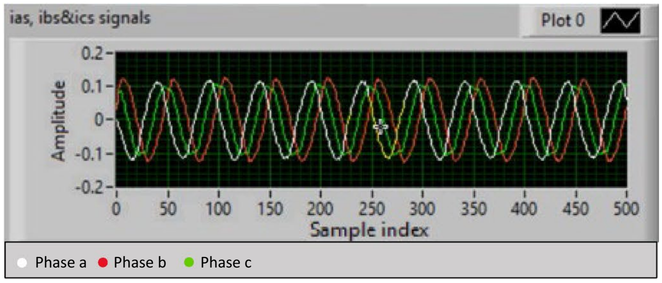
(b) The three cross-correlation coefficients (r_1, r_2, and r_3).

(c) The auto-correlation coefficients (ri_a, ri_b and ri_c) for three phase secondary current signals



(d) Alarm signal in case of correct polarity of three phase current transformers.

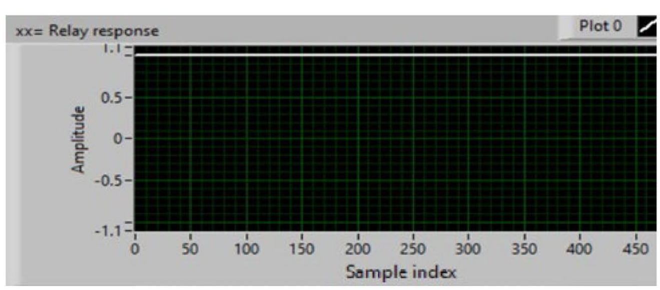
Fig. 4 **a** Three phase secondary current signals at SG load terminals. **b** The three cross-correlation coefficients (r_1, r_2, and r_3). **c** The auto-correlation coefficients (ri_a, ri_b and ri_c) for three phase secondary current signals. **d** Alarm signal in case of correct polarity of three phase current transformers. **a**–**d** The practical results for case study 3



(a) Three phase secondary current signals at SG load terminals.

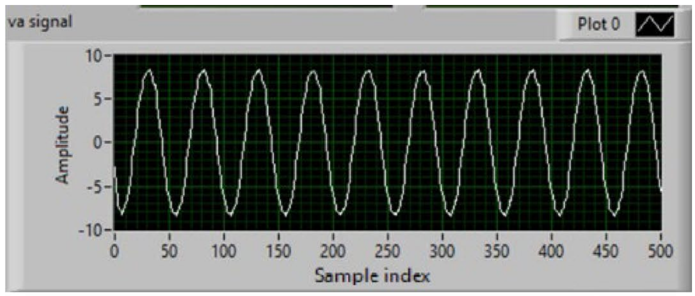
(b) The three cross-correlation coefficients (r_1, r_2, and r_3).

(c) The auto-correlation coefficients (ri_a, ri_b and ri_c) for three phase secondary current signals

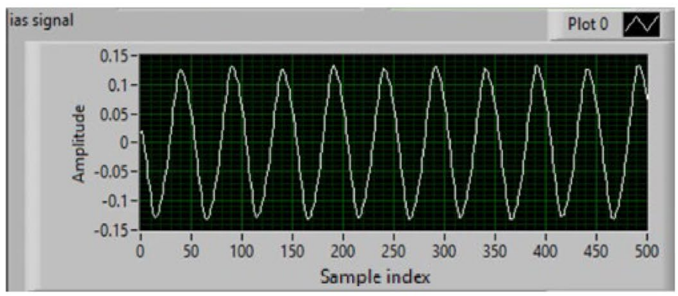


(d) Alarm signal in case of reverse polarity for 'C' phase CT_3.

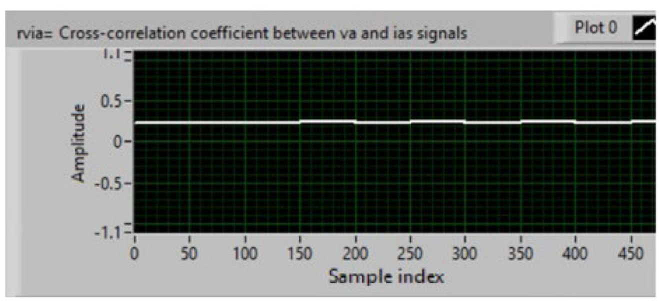
Fig. 5 **a** Three phase secondary current signals at SG load terminals. **b** The three cross-correlation coefficients (r_1, r_2, and r_3). **c** The auto-correlation coefficients (ri_a, ri_b and ri_c) for three phase secondary current signals. **d** Alarm signal in case of reverse polarity for 'C' phase CT_3. **a**–**d** The practical results for case study 4



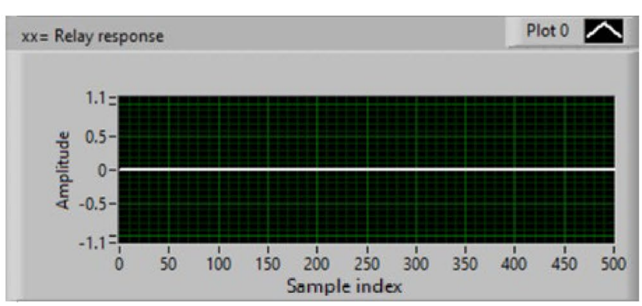
(a) The 'A' phase secondary voltage signal at SG load terminals.



(b) The 'A' phase secondary current signal at SG load terminals.



(c) The cross-correlation coefficient (rvi_a) between the 'A' phase secondary voltage and current signals



(d) Alarm signal in case of correct polarity for VT_1 and CT_1.

Fig. 6 **a** The 'A' phase secondary voltage signal at SG load terminals. **b** The 'A' phase secondary current signal at SG load terminals. **c** The cross-correlation coefficient (rvi_a) between the 'A' phase secondary voltage and current signals. **d** Alarm signal in case of correct polarity for VT_1 and CT_1. **a**–**d** The practical results for case study 5

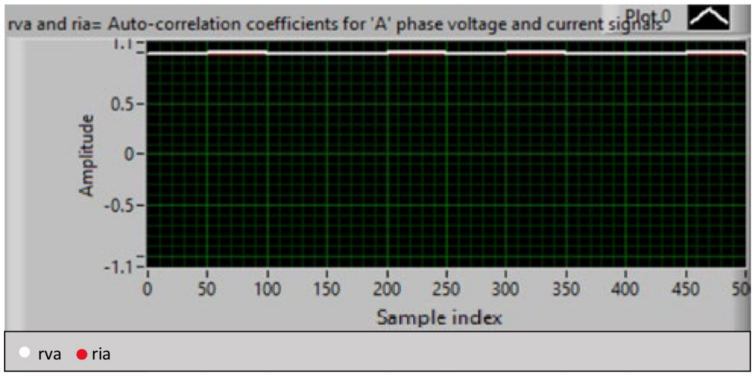


Fig. 7 The auto-correlation coefficient (rv_a and ri_a) for the 'A' phase secondary voltage and current signals

voltage and current signals of '*A*' phase, respectively, are not affected by the reversal of polarity of VT_1 as shown in Fig. 9.

Table 5 lists the values of polarity indices for three phase voltage transformers (Fv_a, Fv_b and Fv_c), three phase current transformers (Fi_a, Fi_b and Fi_c), three single phase voltage and current transformers (Fvi_a, Fvi_b and Fvi_c).

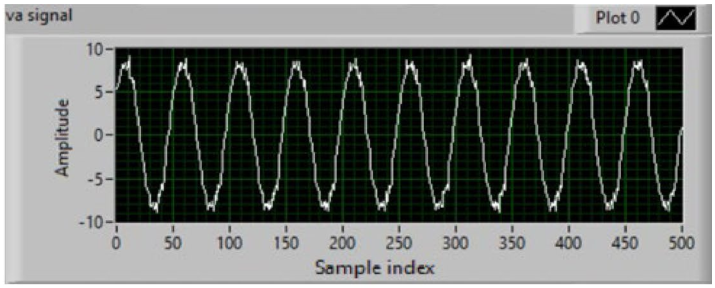
In sum, the polarity of current transformers is extremely important because it determines the direction of the secondary current in relation to the primary current, Moreover, wrong connection of the instrument transformers can cause false operation of the protection relays (such as reverse power, directional overcurrent, restricted earth fault, differential overcurrent relays). Hence, it is vital to ensure that the instrument transformers are connected with the correct polarity.

Features of the proposed digital polarity tester

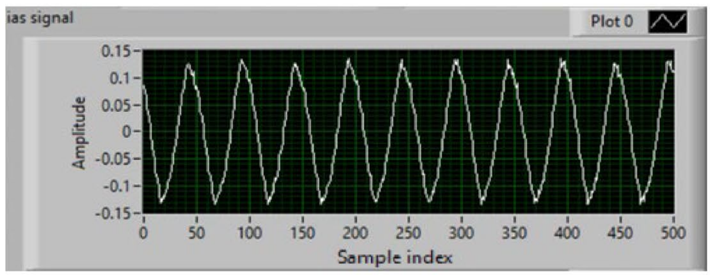
The digital polarity tester, for instrument transformers, based on correlation coefficients which are calculated for voltage and current signals, has the following merits; it is simple, accurate, and reliable. It allows online and continuous monitoring of VT and CT polarity. It can be used as a power, power factor and phase shift meter. It has a closed operating-characteristics normalized between 1 and -1. It is independent on the technical specifications of power system elements and instrument transformers (can be used for various types and ratings). It can be impeded (integrated) in more complex digital relays, meters and fault recorders which are crucial elements in smart grids and substation automation systems.

Conclusions

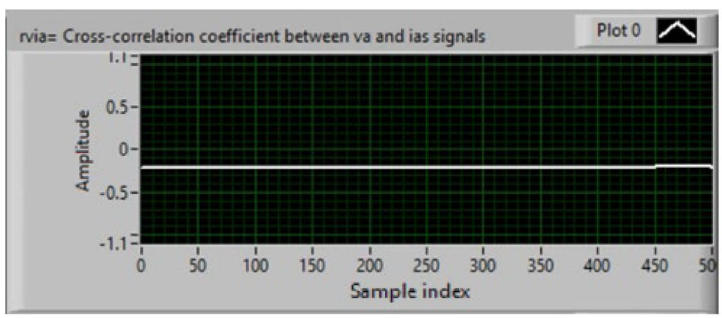
Observing instrument transformer polarity is important in power grids. Incorrect orientation of either the primary or secondary on one or more VT and CT give incorrect power factor, power and energy readings. Reversed CT polarity in protection core may result in mal-operation of protection relay which leads to trip in the case of normal operation or external faults. This paper has developed a correlation-based novel algorithm to detect the correct polarity for instrument transformers, as well as new polarity indices derived from correlation function. The performance of the suggested digital polarity tester for voltage and current transformers has been investigated for



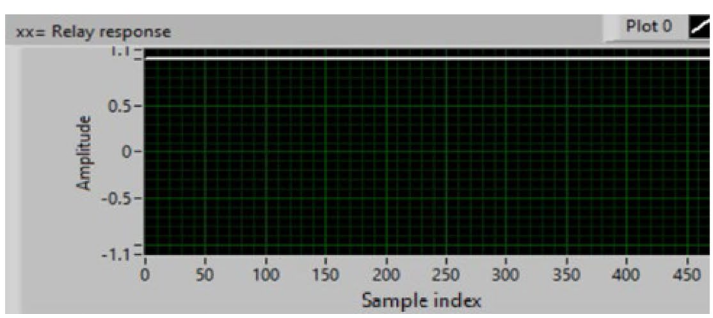
(a) The 'A' phase secondary voltage signal at SG load terminals.



(b) The 'A' phase secondary current signal at SG load terminals.



(c) The cross-correlation coefficient (rvi_a) between the 'A' phase secondary voltage and current signals



(d) Alarm signal in case of reverse polarity for VT_1 (not for CT_1).

Fig. 8 **a** The 'A' phase secondary voltage signal at SG load terminals. **b** The 'A' phase secondary current signal at SG load terminals. **c** The cross-correlation coefficient (rvi_a) between the 'A' phase secondary voltage and current signals. **d** Alarm signal in case of reverse polarity for VT_1 (not for CT_1). **a**–**d** The practical results for case study 6

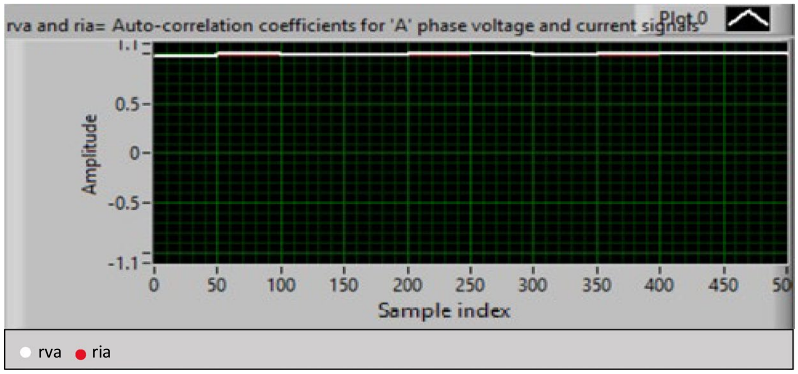


Fig. 9 The auto-correlation coefficient (rv_a and ri_a) for the 'A' phase secondary voltage and current signals

Table 5 Polarity indices for three phase voltage and current transformers for each case study

Case study number	Three phase VTs directionality factor	Three phase CTs directionality factor	Single phase VT and CT directionality factor	Status of instrument transformers polarities
Case study 1	$Fv_a = +1$	$Fi_a = +1$	$Fvi_a = +1$	Correct VTs and CTs polarities and normal operating condition
	$Fv_b = +1$	$Fi_b = +1$	$Fvi_b = +1$	
	$Fv_c = +1$	$Fi_c = +1$	$Fvi_c = +1$	
Case study 2	$Fv_a = +1$	$Fi_a = +1$	$Fvi_a = -1$	Reverse polarity of 'A' phase VT_1
	$Fv_b = -1$	$Fi_b = +1$	$Fvi_b = +1$	
	$Fv_c = -1$	$Fi_c = +1$	$Fvi_c = +1$	
Case study 3	$Fv_a = +1$	$Fi_a = +1$	$Fvi_a = +1$	Correct CTs and VTs polarities and normal operating condition
	$Fv_b = +1$	$Fi_b = +1$	$Fvi_b = +1$	
	$Fv_c = +1$	$Fi_c = +1$	$Fvi_c = +1$	
Case study 4	$Fv_a = +1$	$Fi_a = -1$	$Fvi_a = +1$	Reverse polarity for 'C' phase CT_3
	$Fv_b = +1$	$Fi_b = -1$	$Fvi_b = +1$	
	$Fv_c = +1$	$Fi_c = +1$	$Fvi_c = -1$	
Case study 5	$Fv_a = +1$	$Fi_a = +1$	$Fvi_a = +1$	Correct polarities for 'A' phase VT_1 and CT_1
	$Fv_b = +1$	$Fi_b = +1$	$Fvi_b = +1$	
	$Fv_c = +1$	$Fi_c = +1$	$Fvi_c = +1$	
Case study 6	$Fv_a = +1$	$Fi_a = +1$	$Fvi_a = -1$	Reverse polarity for 'A' phase VT_1
	$Fv_b = -1$	$Fi_b = +1$	$Fvi_b = +1$	
	$Fv_c = -1$	$Fi_c = +1$	$Fvi_c = +1$	

a practical power system model. Three phase voltage and current transformers have installed at the synchronous generator ends for measurement and protection purposes. Voltage and current data, obtained via DAC, has been sent to LABVIEW software for detecting instrument transformer polarity. The obtained practical results have confirmed that the suggested tester is robust, accurate and stable under various operating conditions. It is reliable for discriminating between correct and reverse VTs and/or CTs polarities. Besides it can be integrated with more complex digital fault recorders, relays and meters which are crucial elements in smart grids and substation automation systems. Also, with the same algorithm, it can detect the loss of synchronism, the out-of-step and reverse power events or as an external apparatus to test polarity (digital polarity tester).

Abbreviations

3LG	Three line to ground fault
CT	Current transformer
CTR	Current transformer ratio
DL	Double line fault
DLG	Double line-to-ground fault
Fc	The fundamental frequency
FD	Fault detection
Fs	The sampling frequency
$i_{as}(n)$	Instantaneous secondary current of phase 'A' at sample *'n'*
k	*k*'th frequency component
MCB	Miniature circuit breaker
n	The *n*'th sample
N	Number of samples per window
N_f	Sample number at which the fault occurs
N_s	Number of samples per cycle
R_b	Current transformer burden
R_{CT}	Current transformer secondary winding resistance
R_f	Fault resistance
ri_{ab}	Cross-correlation coefficient between $i_a(n)$ and $i_b(n)$
R_{lead}	Lead resistance
rvi_a	Cross-correlation coefficient between $v_a(n)$ and $i_a(n)$
rv_{ab}	Cross-correlation coefficient between $v_a(n)$ and $v_b(n)$
r_x	Auto-correlation coefficient between each two successive data windows for an electrical signal ($x(n)$)
r_{xy}	Cross-correlation coefficient between each two corresponding windows for the two electrical signals $x(n)$ *and* $y(n)$
S and *X*	Phase designation *A*, *B* or *C*; but they are not similar
Tc	Cycle time period
SG	Synchronous generator
SLD	Single line diagram
SLG	Single line-to-ground fault
t_f	Fault inception time
T_s	Sampling time interval
$v_{as}(n)$	Secondary voltage signal of phase 'A' at sample *'n'*
$v_s(n)$	Voltage signal for every sample *n*; of phase '*S*'
VT	Voltage transformer
VTR	Voltage transformer ratio
$v_x(n)$	Voltage signal for every sample *n*; of phase '*X*'
Δx, Δy and Δz	Auto and cross-correlation setting deviations

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Author contributions
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E. S. Elwakil, participated in resource collecting, experimental setup, comments on results, and revised the final version.

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Declarations

Competing interests
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