Experimental investigations using quadratic-tripping characteristics based on alienation/coherence coefficients of voltage and current signals for synchronous generators protection

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Abstract
A protection scheme is proposed using alienation method derived from coherence model which is a backup protection method for the differential overcurrent protection of synchronous generators. This scheme which is realized by the computational technique based on the alienation coefficients estimated for generator voltage and current signals is considered to be mounted beside the main differential protection system, which operates in the cases that differential protection is unable to detect the internal faults. This novel protection algorithm operates by adjusting the alienation settings of the suggested relay that sends the trip signal to the three-phase circuit breaker of the protected generator. In the proposed method, fault occurrences can be determined regardless of variations of terminal voltage and current in different working states of synchronous generator. This is done by designing new quadratic-tripping characteristics based on alienation limits for the electrical signals. To demonstrate the proposed method, a motor-synchronous generator set with built instrument transformers, for measuring voltage and current data at the generator terminals, are used. Extensive experimental investigations validate the functionality of this novel protection scheme under different abnormal, unbalance and operating conditions for the generator under test.

1 INTRODUCTION

The most important element of a power system is the synchronous generator. As a result, many protection schemes were proposed to protect the synchronous generators against different types of series and shunt faults [1]. Several previous articles presented various schemes for protecting synchronous generators against various types of faults. These schemes were presented for inter-turn short-circuit fault detection, fault type classification or the fault location identification using different techniques such as: total harmonic contents, support vector machine, artificial neural network, fuzzy logic, finite element study and different statistical approaches [1–10]. It was proven by El-Saadawi et al. that most of the AI techniques used in fault diagnosis of synchronous generators including ANN (the most commonly used) have low accuracy in fault diagnosis due to the restriction of over-fitting and long convergence time [1]. In [2], Gopinath et al. used Nuisance Attribute Projection (NAP) algorithm to improve the maximum fault classification accuracy for an inter-turn fault applied to a small working model of a synchronous generator, Pouya Mahdavipour et al. proposed a voltage-controlled overcurrent protection scheme which is a backup protection of differential relay in [3], while in [11], Cofiele et al. suggested an adaptive overcurrent relay to reduce the mean operating time compared with conventional overcurrent schemes. Liang Che; Ustun, et al. considered sensing low fault currents and time delay in microgrids [12,13], respectively. Yadaiah et al. proposed a technique to detect and classify internal and external faults of synchronous generator in [14]. The sensitivity and operating time of protective relay become an issue when DGs are inserted [15]. Many authors discussed adaptive and AI techniques of overcurrent protection of DGs and microgrids [16–20]. The authors in [21] utilized the machine model for simulating stator internal faults and...
presented a 100% stator-ground protection based on the third harmonic voltage on the neutral and terminals of the machine. Paper [22] developed an analytical method to detect, classify, and locate the internal faults, namely phase-to-ground faults and turn-to-turn faults, in the synchronous generator stator winding based on harmonic components of the terminal voltage waveforms, where Decision Tree (DT) is employed to extract the third and the fourth harmonic components of the terminal voltage waveforms and the fundamental component of the residual voltage signal, which used not only all the turn-to-turn faults and the number of the shorted turns can be determined but also the faulty phase to-ground can be detectable. In [23], the authors suggested a new approach to interpret the voltage unbalance cases using the expression of voltage unbalance factor (VUF). In [24], Shweta et al. proposed an analytical technique based on coherence coefficient and Lagrangian function to separate the out of step generator and to give information about the level of instability of the system. In [25], Vahidnia et al. used the coherence function and the angle of cross-spectral density function to assess whether the interconnected generators are positively or negatively coherent and assign them different machine groups. In [26,27], Elsadd et al. presented new adaptive techniques in the first article with the aim to increase the reliability of the generator-transformer unit overall differential protection with use of the capability curves, also presented formulas to calculate the reliability, dependability, and security percentage of the protective relay, while in the second article the authors proposed an adaptive optimum coordination for deregulated distribution networks considering the change in the network topology including parallel feeders. In this paper, a backup protection scheme for synchronous generator is proposed to operate and to send a trip signal to the generator breakers in conditions that the main protection scheme, which is the high-speed differential overcurrent protection, is unable to detect the internal fault. In this protection scheme, alienation coefficients derived from coherence coefficients, calculated for generator voltage and current signals, is used as the final decision maker and sets the alienation setting of the proposed relay that sends the trip signal to the generator breaker(s). This paper is organized as follows: In Section 2, the alienation-based protection scheme of the synchronous generator, with all the details, is given. In Section 3, the motor-generator set under test with its instrument transformers are presented. In Section 4, the experimental results are given. In Section 5, the proposed technique features have been listed. In Section 6, the conclusions have been made.

2 | PROTECTION SCHEME USING ALIENATION METHOD

2.1 | Basic principle

There are a number of parameters that change with fault occurrence in synchronous generator. RMS values of the terminal voltages will drop and RMS values of the terminal currents will increase under short-circuit and overload conditions. In addition, the fault event may lead to a disturbance in frequencies and phase angle shifts measured for three phase voltage and current signals. Moreover, the fault may cause a variation in the symmetry and shape of sinusoidal waveforms or an unbalance between the three-phase voltage/current signals [23]. This fact can be used to diagnose the fault in cases that none of the three phase currents contain a D.C. component. Because of the unpredictable time of the fault occurrence, and therefore unknown state of the voltage and current signals at that random time, RMS value of the voltage or current cannot be a reliable parameter for diagnosing the fault. For all types of possible faults of the generator stator windings, terminal currents may contain D.C. components or not. Hence, a numerical method, based on the alienation concepts, is proposed; besides novel closed-tripping characteristics is developed for synchronous generators protection. In this article, the alienation coefficients are computed using the measured three phase voltage and current signals, which are obtained from coherence coefficients. A coherence coefficient is a statistical method that can be used to investigate the relationship, as a function of frequency, between any two signals or data sets. The coherence coefficient, sometimes called Magnitude-Squared Coherence (MSC), estimated between the two signals is a real value that lies from ‘0’ to ‘+1’ [24,25]. Therefore, the alienation coefficient is ranged between the two values of ‘+1’ and ‘0’. The alienation approach can be used for discriminating normal, abnormal, balance and unbalance conditions of three phase voltage and current signals measured at the load side of SG stator windings.

2.2 | Coherence coefficients calculation

There are two types of coherence coefficients used in this paper. One coherence coefficient is used for the same electrical signal of each phase which is named as ‘auto-coherence’. The auto-coherence can monitor the disturbance condition in each voltage/current signal. The other type of coherence coefficients is used for two different electrical signals of one phase or two phases which is denoted as ‘cross-coherence’. The cross-coherence can compare the unsymmetrical condition between each two voltage or two current signals for two different phases or differentiate between voltage and current signals for the same phase.

2.2.1 | Calculation of the cross-coherence coefficients for three phase voltage signals

To estimate the cross-coherence coefficient \( C_{v_xk} \) between the two sampled voltage signals \( v_x(n) \) and \( v_y(n) \) of the two different phases ‘S’ and ‘X’, respectively, the following equation can
be used:

\[
C_{r_{sx}}(k) = \left( \frac{\sum_{n=0}^{N-1} V_{x1}(k) \times V_{x1}(k) + V_{x2}(k) \times V_{x2}(k)}{\sum_{n=0}^{N-1} [(V_{x1}(k))^2 + (V_{x2}(k))^2]} \right)^2 + \left( \frac{\sum_{n=0}^{N-1} V_{x1}(k) \times V_{x2}(k) - V_{x2}(k) \times V_{x1}(k)}{\sum_{n=0}^{N-1} [(V_{x1}(k))^2 + (V_{x2}(k))^2]} \right)^2
\]  

(1)

where,

\[
V_{x1}(k) = \sum_{n=0}^{N-1} v_x(n) \cdot \cos \left( \frac{2\pi k n}{N} \right)
\]  

(2)

\[
V_{x2}(k) = \sum_{n=0}^{N-1} v_x(n) \cdot \sin \left( \frac{2\pi k n}{N} \right)
\]  

(3)

\[
V_{sx1}(k) = \sum_{n=0}^{N-1} v_x(n) \cdot \cos \left( \frac{2\pi k n}{N} \right)
\]  

(4)

\[
V_{sx2}(k) = \sum_{n=0}^{N-1} v_x(n) \cdot \sin \left( \frac{2\pi k n}{N} \right)
\]  

(5)

2.2.2 Calculation of the cross-coherence coefficients for three phase current signals

The following equation can be used for estimating the cross-coherence coefficient \( (C_{r_{sx}}(k)) \) between the two discrete current signals \( (i_s(n) \) and \( i_x(n)) \) of the two different phases 'S' and 'X', respectively:

\[
C_{r_{sx}}(k) = \left( \frac{\sum_{n=0}^{N-1} i_1(k) \times i_{s1}(k) + i_2(k) \times i_{s2}(k)}{\sum_{n=0}^{N-1} [(i_1(k))^2 + (i_2(k))^2]} \right)^2 + \left( \frac{\sum_{n=0}^{N-1} i_1(k) \times i_{s2}(k) - i_2(k) \times i_{s1}(k)}{\sum_{n=0}^{N-1} [(i_1(k))^2 + (i_2(k))^2]} \right)^2
\]  

(6)

2.2.3 Calculation of the cross-coherence coefficient between phase voltage and current signals

The following equation can be applied for evaluating the cross-coherence coefficient \( (C_{r_{is}}(k)) \) between the sampled phase voltage and current signals \( (v_i(n) \) and \( i_s(n)) \) for the phase 'S':

\[
C_{r_{is}}(k) = \left( \frac{\sum_{n=0}^{N-1} v_1(k) \times i_1(k) + v_2(k) \times i_2(k)}{\sum_{n=0}^{N-1} [(v_1(k))^2 + (v_2(k))^2]} \right)^2 + \left( \frac{\sum_{n=0}^{N-1} v_1(k) \times i_2(k) - v_2(k) \times i_1(k)}{\sum_{n=0}^{N-1} [(v_1(k))^2 + (v_2(k))^2]} \right)^2
\]  

(7)

Where,

\[
i_1(k) = \sum_{n=0}^{N-1} i_1(n) \cdot \cos \left( \frac{2\pi k n}{N} \right)
\]  

(8)

\[
i_2(k) = \sum_{n=0}^{N-1} i_2(n) \cdot \sin \left( \frac{2\pi k n}{N} \right)
\]  

(9)
2.2.4 Calculation of auto-coherence coefficient for phase current signal

The auto-coherence coefficient is computed for each phase current signal. The auto-coherence coefficient ($Ci_j(k)$), calculated between each two successive data windows shifted from each other by one-cycle interval of the same current signal ($i_j(n - N_i)$ and $i_j(n)$) for each ‘$j$’ phase, is formulated as follows:

$$Ci_j(k) = \frac{\left[ \left( \sum_{m=0}^{N-1} I_{ij}(k) \times I_{ij}(k) + I_{ij}(k) \times I_{ij}(k) \right)^2 + \left( \sum_{m=0}^{N-1} I_{ij}(k) \times I_{ij}(k) - I_{ij}(k) \times I_{ij}(k) \right)^2 \right]}{\sum_{m=0}^{N-1} [(I_{ij}(k))^2 + (I_{ij}(k))^2] \times \sum_{m=0}^{N-1} [(I_{ij}(k))^2 + (I_{ij}(k))^2]}$$

Where,

$$I_{ij}(k) = \sum_{n=0}^{N-1} [i_j(n - N_i) \cdot \cos \left( \frac{2\pi kn}{N} \right)]$$

$$I_{is}(k) = \sum_{n=0}^{N-1} [i_j(n - N_i) \cdot \sin \left( \frac{2\pi kn}{N} \right)]$$

2.2.5 Calculation of auto-coherence coefficient for phase voltage signal

The auto-coherence coefficient is computed for each phase voltage signal. The auto-coherence coefficient ($Cv_j(k)$), computed between each two successive data windows shifted from each other by one-cycle interval of the same voltage signal ($v_j(n - N_j)$ and $v_j(n)$) for each ‘$j$’ phase, is given in the following mathematical formula:

$$Cv_j(k) = \frac{\left[ \left( \sum_{m=0}^{N-1} V_{ij}(k) \times V_{ij}(k) + V_{ij}(k) \times V_{ij}(k) \right)^2 + \left( \sum_{m=0}^{N-1} V_{ij}(k) \times V_{ij}(k) - V_{ij}(k) \times V_{ij}(k) \right)^2 \right]}{\sum_{m=0}^{N-1} [(V_{ij}(k))^2 + (V_{ij}(k))^2] \times \sum_{m=0}^{N-1} [(V_{ij}(k))^2 + (V_{ij}(k))^2]}$$

Where,

$$V_{ij}(k) = \sum_{n=0}^{N-1} [v_j(n - N_j) \cdot \cos \left( \frac{2\pi kn}{N} \right)]$$

$$V_{is}(k) = \sum_{n=0}^{N-1} [v_j(n - N_j) \cdot \sin \left( \frac{2\pi kn}{N} \right)]$$

2.3 Alienation coefficients calculation

The alienation coefficient is defined as the complement of Magnitude-Squared Coherence (MSC) or coherence coefficient, and its value is bounded between ‘+1’ and ‘0’ [24,25]. Thus, there are two types of alienation coefficients used in the suggested algorithm. The first type is auto-alienation coefficient that is derived from the auto-coherence coefficient, which is used for the same electrical signal of each phase. Whereas the other type of alienation coefficients is cross-alienation coefficient that is deduced from the cross-coherence coefficient, which is used for two different electrical signals of one or two phase(s).

$$Av_{ij}(k) = 1 - Cv_{ij}(k)$$

$$Av_{s}(k) = 1 - Cv_{s}(k)$$

As mentioned before, the coherence and alienation coefficients assess a relationship between any two variables in the frequency domain. In the following table, some properties of alienation/coherence coefficient are listed; where, the benefit of each property of the coefficient is mentioned next to each property of them in the table.

In this paper, nine cross-alienation coefficients ($Av_{ijd}$, $Av_{ijo}$, $Av_{ida}$, $Av_{idb}$, $Av_{ida}$, $Av_{idp}$, $Av_{ids}$, $Av_{idi}$, and $Av_{ild}$) and six auto-alienation coefficients ($Av_{id}$, $Av_{isp}$, $Av_{idf}$, $Av_{idp}$, $Av_{idh}$, and $Av_{idt}$) are computed and applied in the developed algorithm. The 15 alienation coefficients based-proposed technique is able to identify the normal/balance operating (i.e. no-fault state) and
abnormal/unbalance conditions (such as overload, series and shunt faults, and CT saturation situation) using the rules listed in Table 2.

2.4 Protection algorithm procedure

As shown in Figure 1, the flow chart of the proposed protection algorithm, based on the fifteen alienation factors deduced from the coherence factors, works as explained below:

2.5 Tripping characteristics

Figure 2(a) presents three types of closed-tripping characteristics for the voltage, current and power factor unbalance condition, respectively. The tripping characteristics depend on the setting deviations of their cross-alienation coefficients with respect to their ideal values. They are restricted between the two values of (0.75 – Δx, 0.75 + Δy), (0.75 – Δy, 0.75 + Δy), and (0.0 – Δy, 0.0 + Δy) in the case of ideal balance and acceptable unbalance for the three quantities of the three phases, respectively. In addition to that each characteristic has two zones: (I) a blocking zone (i.e. preventing the operation of the proposed algorithm) in the case of normal/balance condition, and (II) a tripping zone (i.e. operating the proposed protection algorithm for isolating the protected element) in the case of unbalance state. Figure 2(b) develops closed-tripping characteristics for the voltage and current disturbance, respectively. Each characteristic is based on the setting deviations of their auto-alienation coefficients compared to their ideal values. They are bounded between the two values of (0.0 Δv) and (0.0 Δv) in the case of normal operation for the voltage and current signals, respectively, measured at the three terminals of synchronous generator stator windings. Also, each characteristic possesses two zones: (I) a blocking zone in the case of normal operating condition, and (II) a tripping zone in the case of abnormal/fault condition.

In the operating characteristics, shown in Figure 2(a) and (b), the index ‘Δ’ denotes to alienation coefficient, ‘r’ is voltage variable, ‘r’, ‘r’ and ‘x’ are the designation of three different phases, and the selected values of the alienation setting deviations (Δr, Δr, Δr) and Δx are 0.1, 0.1, 0.1, 0.1 and 0.75, respectively. These deviations are carefully selected according to the prevailed conditions, the acceptable overload currents, decent harmonics and temporary faults which occur in power system to prevent incorrect operation of the protection function. It is noted that the setting deviation (Δx) is large because of the low power factor of the used load in a system under test.

In the case of acceptable unbalance due to the overload condition, the RMS value of the terminal currents rises and
| Module type | The used electrical signals | Alienation coefficients limits | Power system status (balance/unbalance or normal/abnormal condition) | The proposed method action (blocking/tripping) |
|-------------|----------------------------|-------------------------------|---------------------------------------------------------------|------------------------------------------------|
| Module (1) to detect the voltage unbalance condition using the cross-alienation coefficients for the voltage signals | \( r_a, r_b \) and \( r_b, r_c \) | \( 0.75 - \Delta x \geq A_{ar}, 0.75 - \Delta x \geq A_{br}, 0.75 - \Delta x \geq A_{cr}, 0.75 - \Delta x \geq A_{dr} \) | Voltage unbalance | Alarm/tripping CBs |
| Module (2) to detect the current unbalance condition using the cross-alienation coefficients for the current signals | \( i_a, i_b \) and \( i_b, i_c \) | \( 0.75 + \Delta y \geq A_{ia}, 0.75 + \Delta y \geq A_{ib}, 0.75 + \Delta y \geq A_{ic} \) | Current unbalance | Alarm/tripping CBs |
| Module (3) to detect the disturbance of power factor using the cross-alienation coefficients between voltage and current signals | \( r_a, r_b \) and \( i_a, i_b \) | \( 0 \leq \Delta v_{ia} \leq \Delta x, 0 \leq \Delta v_{ib} \leq \Delta y, 0 \leq \Delta v_{ic} \leq \Delta z \) | Balance and Proper power factor | Blocking |
| Module (4) to detect the voltage disturbance condition using the auto-alienation coefficient for each phase voltage signal | \( r_a, r_b \) and \( v_a, v_b \) | \( 0 \leq \Delta v_{ia} \leq \Delta x, 0 \leq \Delta v_{ib} \leq \Delta y, 0 \leq \Delta v_{ic} \leq \Delta z \) | Normal voltage | Blocking |

The selected values of the alienation setting deviations \( \Delta u, \Delta w, \Delta x, \Delta y \) and \( \Delta z \) are 0.1, 0.1, 0.1, 0.1 and 0.75, respectively.
| Module type | The used electrical signals | Alienation coefficients limits | Power system status (balance/unbalance or normal/abnormal condition) | The proposed method action (blocking/tripping) |
|-------------|-----------------------------|-------------------------------|-------------------------------------------------|---------------------------------------------|
| Module (5) to detect the current disturbance condition using the auto-alienation coefficient for each phase current signal | $v_n$ (n) and $v_i$ (n) | $I_a (n) \leq \Delta w$ | Normal current | Blocking |
| | $v_i$ (n) and $v_a$ (n) | $I_b (n) \leq \Delta w$ and $I_c (n) \leq \Delta w$ | | |
| | $i_a (n)$ and $i_b (n)$ | $0 \leq I_a (n) \leq \Delta w$ | Abnormal current | Alarm/tripping CBs |
| | $i_b (n)$ and $i_c (n)$ | $0 \leq I_b (n) \leq \Delta w$ and $I_c (n) \leq \Delta w$ | | |
| | $i_c (n)$ and $i_a (n)$ | $\Delta w \leq I_a (n) \leq l$ | | |
| | $i_a (n)$ and $i_c (n)$ | $\Delta w \leq I_b (n) \leq l$ or $\Delta w \leq I_c (n) \leq l$ | | |
FIGURE 1 Flow chart of the proposed alienation-based algorithm for synchronous generator protection

Voltages drop to approximately 90% of the nominal value, besides the phase shifts between the three phase angles are slightly changed with respect to the ideal phase shifting. Regarding these facts, the conventional overcurrent relay sends the trip signal to the generator circuit breaker(s) because of the increment of the RMS value of the terminal currents. So, the setting of the traditional relay must be suitable, and the isolation of the generator must be avoided through the overcurrent protection. Also, this problem can be prevented via the convenient values of the alienation setting deviations of the
The DAC and LABVIEW software package are used for testing the proposed algorithm for protecting the three-phase synchronous generator against abnormal and unbalance situations. In this study, the selected size of data window is one cycle (i.e. 50 samples per cycle), and the full time of display is 0.2 s (i.e. the total number of samples \(N_t\) per the display time is 500 samples). The following section offers experimental results for different cases of normal operating and fault types.
FIGURE 3  Motor-generator set under test (a) experimental model photo, (b) schematic diagram.
4.1 Case 1: No fault condition (25% current unbalance)

In this case, the generator is working properly without any faults. Initially, the RMS values, measured using a digital multi-meter, of three phase primary currents for the generator are: $I_a = 2.7 \times (5/200) = 0.085\ A$, $I_b = 2.1 \times (5/200) = 0.074\ A$, $I_c = 2.5 \times (5/200) = 0.095\ A$. Also, the RMS values of the three phase primary voltages measured for the generator terminals are: $V_a \approx V_b \approx V_c \approx 230\ V$, thus the peak values of the three phase secondary voltages are: $v_{as} \approx v_{bs} \approx v_{cs} \approx 23 \times (5/220) \times 1.41 = 7.37\ V$. Three phase current and voltage waveforms in normal operating state (i.e. without fault occurrence) are displayed in Figure 4(a) and (b), respectively, while the cross-alienation coefficients calculated for three phase current signals are shown in Figure 4(c) with slight deviation due to the decent unbalance of instrumentation CTs of the three phases. The cross-alienation coefficients for three phase voltage signals are shown in Figure 4(d). All the above cross-alienation factors are approximately equal to $+0.75$ at normal operation with the acceptable unbalance for current/voltage curves. Figure 5(a) and (b) shows the auto-alienation coefficients for three phase current signals and three phase voltage signals, respectively, with a value of zero. Whereas the cross-alienation coefficients between each phase voltage and current signals are shown in Figure 5(c) with a value close to $+0.75$ at normal operation and no trip command as shown in Figure 5(d). In this case, it is evident clear that the fifteen alienation coefficients affirm the healthy condition, and their values are settled in the blocking zones of the operating characteristics.

4.2 Case 2: ‘C’ phase series fault condition (MCB3 opening)

In this case, “C” phase is manually open circuited, while all other conditions are the same as case 1. The three phase current and voltage waveforms are shown in Figure 6(a) and (b). Figure 6(c) shows the cross-alienation coefficients between each two phase currents; it is clear that the cross-alienation coefficient between the two currents of the healthy phases is zero, while the cross-alienation coefficient between any of them and the faulty phase current is nearly $+1$. Figure 6(d) presents the cross-alienation coefficients between each two phase voltages with a slight difference due to the open circuit of the “C” phase and the unbalance of instrumentation VTs. It is seen that the cross-alienation coefficient between the two voltages of the healthy phases is $+0.6$, while the cross-alienation coefficient between any of them and the faulty phase voltage is nearly $+0.85$. In Figure 7(a) and (b), the auto-alienation coefficients for the three phase currents and the three phase voltages are shown, respectively, revealing the only different value of roughly $+1$ for the faulty “C” phase current, while the remaining auto-alienation coefficients are about zero. The cross-alienation coefficients between each
FIGURE 4  Experimental results for case 1. (a) Three phase currents in normal working state, (b) three phase voltages in normal working state, (c) three phase cross-alienation coefficients calculated for three phase current signals, (d) three phase cross-alienation coefficients calculated for three phase voltage signals.

FIGURE 5  Experimental results for case 1 (continued). (a) Three phase auto-alienation coefficients calculated for three phase current signals, (b) three phase auto-alienation coefficients calculated for three phase voltage signals, (c) three phase cross-alienation coefficients calculated between three phase voltage and current signals, (d) blocking signal in normal working state.

FIGURE 6  Experimental results for case 2. (a) Three phase currents in series fault state, (b) three phase voltages in series fault state, (c) three phase cross-alienation coefficients calculated for three phase current signals, (d) three phase cross-alienation coefficients calculated for three phase voltage signals.
phase voltage and its current are shown in Figure 7(c), also with a distinguished value for the faulty phase. Their values are approximately +1 for the two healthy phases, while the cross-alienation coefficient is about +0.4 for the faulty phase. In Figure 7(d), the trip order is high, indicating the detection of the series fault for "C" phase. In this test, it is clear that some alienation coefficients confirm the faulty state, and their values are located inside the tripping zones of the operating characteristics.

4.3 | Case 3: ‘A and C’ phases series fault condition) (MCB3 and MCB5 opening)

In this case, both phases “A” and “C” are manually open-circuited. Figure 8(a) and (b) depicts the three phase currents and the three phase voltages, respectively, at the instants of fault occurrence and clearing. It is noted that the open circuit of the two phases is done manually which explains the time delay between the current signals and the voltage signals of the two faulty phases, this effect is equivalent to a DL series fault followed by a SL series fault. Figure 8(c) and (d) presents the cross-alienation coefficients between each two phase currents and the cross-alienation coefficients between each two phase voltages, respectively. The auto-alienation coefficients of the three phase currents and three phase voltages are shown in Figure 9(a) and (b) with variation of the coefficients during the fault period. The cross-alienation coefficients between each phase voltage and its current are represented in Figure 9(c) while the trip command is shown in Figure 9(d) indicating that the algorithm managed to detect the series fault condition in both phases “A” and “C”. In this case, it is seen that all
alienation coefficients assure the faulty condition and their values are stationary inside the tripping zones of the closed-tripping characteristics.

4.4 Case 4: SLN (B-N) shunt fault condition

In this test, the fault type is SLN (B-N) shunt fault. The fault is located at the load ends of the synchronous generator under test. Figures 10 and 11 present the practical results for case 4. Figure 10(a) illustrates the three phase secondary current signals at the SG load terminals. Figure 10(b) depicts the three phase secondary voltage signals at SG load sides. During the period of the first two cycles from the beginning of display time, the waveforms of three phase voltages and currents are sinusoidal and their magnitudes are normal, while their waveforms and values are disturbed during the fault time span. The instantaneous values of the three phase currents rise and the generated values of three phase voltages drops with respect to their nominal values during the fault time. During the fault interval, the peak values of the three phase secondary voltage signals are lower than 7.0 V, while the peak values of the three phase secondary current signals are greater than 0.2 A. Figure 10(c) manifests the three phase cross-alienation coefficients calculated between each two phase current signals. In this case, it is evident that the values of these coefficients are steady.

FIGURE 9 Experimental results for case 3 (continue). (a) Three phase auto-alienation coefficients calculated for three phase current signals, (b) three phase auto-alienation coefficients calculated for three phase voltage signals, (c) three phase cross-alienation coefficients calculated between three phase voltage and current signals, (d) tripping signal in series fault state.

FIGURE 10 Experimental results for case 4. (a) Three phase currents in shunt fault state, (b) three phase voltages in shunt fault state, (c) three phase cross-alienation coefficients calculated for three phase current signals, (d) three phase cross-alienation coefficients calculated for three phase voltage signals.
and close to +0.75 during the period of the first two cycles, but their values are not constant during the remaining display time. Figure 10(d) introduces the three phase cross-alienation coefficients calculated between each two phase voltage signals. Also, it is seen that the values of these coefficients are fixed and close to +0.75 during the distance of the first two cycles, while their values are not stationary during the fault time. Figure 11(a) exhibits the three phase auto-alienation coefficients computed for each phase current signals. Figure 11(b) plots the three phase auto-alienation coefficients calculated for each phase voltage signals. As shown in Figure 11(a) and (b), it is clear that the six auto-alienation coefficients computed for current and voltage signals are steady during the normal operation (i.e. the first two cycles), while they rise instantaneously with the fault starting. Figure 11(c) describes three phase cross-alienation coefficients calculated between each phase voltage and current signals. It is seen that the values of the three phase coefficients change suddenly at the instant of fault inception, as presented in Figure 10(c), where they are constant and close to +0.8 during the normal operation condition; whereas their values are changed from +1.0 to +0.2 during the fault time. Figure 11(d) displays the tripping signal which is a high value of +1 in the case of SLN shunt fault. In this case, it is noticed that all alienation coefficients prove the faulty situation, and their values are inside the tripping zones of the closed-operating characteristics. The experimental results confirm that the proposed protection algorithm is accurate, fast and reliable for identifying the abnormal/unbalance condition for three phase voltage and current signals.

4.5 Case 5: SLN (C-N) shunt fault condition with arc

In this case, a shunt fault is conducted between phase “C” and the neutral “N” at the output terminals of the synchronous generator. Figures 12 and 13 clarify the generated results from the protection algorithm for case 5 (SLG (C-N) shunt fault). Figure 12(a) and (b) show the three phase current and three phase voltage signals, respectively. Figure 12(c) illustrates the cross-alienation coefficients between each two phase currents while the cross-alienation coefficients between each two phase voltages are shown in Figure 12(d) with the clear variation of the calculated coefficients at the instant of fault occurrence. Figure 13(a) and (b) depicts the auto-alienation coefficients of the three phase currents and the three phase voltages, respectively. The variation of the calculated coefficients before and after fault occurrence indicates that the relay detected the fault/unbalance successfully. Figure 13(c) shows the cross-alienation coefficient calculated between each phase voltage and its current. Whereas the trip signal is showing high value, as seen in Figure 13(d), to indicate that the proposed algorithm managed to identify the fault/unbalance condition. In this case, it is intelligible that all alienation coefficients affirm the fault occurrence, and their values are stable inside the tripping zones of the quadratic tripping characteristics.

4.6 Case 6: DL (A-B) shunt fault condition

In this case, both phases “A” and “B” are shorted. Figure 14(a) and (b) shows the three phase currents and three phase voltages, respectively. The cross-alienation coefficients between each two phase currents are shown in Figure 14(c), while the cross-alienation coefficients between each two phase voltages are shown in Figure 14(d). The auto-alienation coefficients of the three phase currents and the three phase voltages are shown in Figure 15(a) and (b) with changes in the values of calculated coefficients at the instant of fault occurrence. In Figure 15(c), the cross-alienation coefficients between each phase voltage and its current are shown with distinguished values of the coefficients for the two faulty phases. Figure 15(d) offers the tripping
FIGURE 12  Experimental results for case 5. (a) Three phase currents in shunt fault state, (b) three phase voltages in shunt fault state, (c) three phase cross-alienation coefficients calculated for three phase current signals, (d) three phase cross-alienation coefficients calculated for three phase voltage signals.

FIGURE 13  Experimental results for case 5 (continue). (a) Three phase auto-alienation coefficients calculated for three phase current signals, (b) three phase auto-alienation coefficients calculated for three phase voltage signals, (c) three phase cross-alienation coefficients calculated between three phase voltage and current signals, (d) tripping signal in shunt fault state.

FIGURE 14  Experimental results for case 6. (a) Three phase currents in shunt fault state, (b) three phase voltages in shunt fault state, (c) three phase cross-alienation coefficients calculated for three phase current signals, (d) three phase cross-alienation coefficients calculated for three phase voltage signals.
signal in the event of $DL_{(A-B)}$ shunt fault. In this case, it is manifested that all alienation coefficients assert the fault occurrence, and their values are concentrated in the tripping zones of the quadratic tripping characteristics.

### 4.7 Case 7: DL shunt fault (A-C) with CT saturation condition

In the following case, also the two phases “A” and “C” are shorted, but this time the instrumentation CTs and VTs are saturated as could be seen in Figure 16(a) and (b). In spite of CT saturation, the cross-alienation coefficients could detect the abnormal/unbalance condition between each two phase currents, as depicted in Figure 16(c) and between each two phase voltages, as given in Figure 16(d). Figure 17(a) and (b) shows the auto-alienation coefficients for the three phase currents and the three phase voltages, respectively. In Figure 17(c), the cross-alienation coefficients between each phase voltage and its current are shown with clear deviation from the normal operation condition which means that the algorithm detected a fault/unbalance condition and sent a trip order to the circuit breaker as shown in Figure 17(d). In this experiment, it is plain that all alienation coefficients ascertain the fault event, and their values are settled in the tripping zones of the closed-tripping characteristics.

From the above practical results and other experimental verifications, it is concluded that all alienation coefficients
are located inside the blocking zones of the closed-operating characteristics during the normal operating conditions, while most these coefficients are concentrated inside the tripping zones during the abnormal/unbalance conditions (such as series faults, shunt faults and CT saturation). Moreover, the proposed protection scheme based on the alienation/coherence method is an acceptable solution in detection and assessment of the different operating, unbalance and abnormal conditions for the synchronous generator under test. Hence the performance of the proposed protection algorithm is investigated as a backup relay for generators protection using the alienation coefficients (derived from the coherence coefficients) computed for three phase voltage and current data.

In this study, the performance of the proposed protection scheme was monitored over a period of nearly 3 months. It was found that the protection scheme operated 85 times, out of which 82 were correct trips. The relay failed to issue trip decision on two occasions. In all cases of normal operating conditions, the protection scheme was hold/blocked 35 times without any maloperation time. The percentages of accuracy, dependability, security and reliability of the proposed protective relay can be computed under both faults and measurement errors utilizing the formulae presented in articles [26,27], as given in Table 4:

- Total number of normal operating conditions = 35
- Total number of trips = 85

### TABLE 4 Computation of accuracy, dependability, security and reliability percentages of the proposed relay

| Proposed algorithm (SG backup protection) | Number of tests | Maloperation times number |
|-----------------------------------------|----------------|--------------------------|
| Power model condition                   |                |                          |
| Fault                                   | 85             | 3                        |
| Normal operation                        | 35             | 0                        |
| Total number of tests                   | 120            | Total number of maloperation = 3 |
| Accuracy (%)                            | = ((120− 2− 3)/120) × 100 = 95.83% |
| Total number of trips                   | = 85           |
| Number of correct trips                 | = 82           |
| The times number of the relay failed to issue trip decision | = 2 |
| Number of desired trips                 | = 82 + 2 = 84 |
| Number of incorrect trips               | = 85 − 82 = 3 |
| Number of desired trips + number of incorrect trips | = 84 + 3 = 87 |
| Dependability (%)                       | = (82/84) × 100 = 97.62% |
| Security (%)                            | = (82/85) × 100 = 96.47% |
| Reliability (%)                         | = (82/87) × 100 = 94.25% |

### FIGURE 17 Experimental results for case 7 (continue). (a) Three phase auto-alienation coefficients calculated for three phase current signals, (b) three phase auto-alienation coefficients calculated for three phase voltage signals, (c) three phase cross-alienation coefficients calculated between three phase voltage and current signals, (d) tripping signal in shunt fault state.
Number of correct trips = 82
Number of incorrect trips = 85 - 82 = 3
Number of desired trips + Number of incorrect trips = 84 + 3 = 87

\[ (I) \text{ } \% \text{ Dependability} = \frac{\text{Number of correct trips}}{\text{Number of desired trips}} \times 100 \]

\[ (I) \text{ } \% \text{ Dependability} = \frac{82}{84} \times 100 = 97.62 \%
\]

\[ (II) \text{ } \% \text{ Security} = \frac{\text{Number of correct trips}}{\text{Total Number of trips}} \times 100 \]

\[ (II) \text{ } \% \text{ Security} = \frac{82}{85} \times 100 = 96.47 \%
\]

\[ (III) \text{ } \% \text{ Reliability} = \frac{\text{Number of correct trips}}{\text{Number of desired trips} + \text{Number of incorrect trips}} \times 100 \]

\[ (III) \text{ } \% \text{ Reliability} = \frac{82}{84 + 3} \times 100 = 94.25 \%
\]

Note that even though dependability and security are individually above 95%, overall reliability is lower than 95% (only 4.25%).

5 | ALIENATION/COHERENCE-BASED PROTECTION ALGORITHM FEATURES

The developed protection technique based on the alienation derived from coherence concept has the following merits:

1. The abnormal and unbalance conditions, for the three phase voltage and current signals, can be continually monitored and identified quickly and accurately using the alienation coefficients estimated for the electrical signals,
2. The size of data window can be tuned to get fast response, where it is selected to be one cycle or sub-cycle for most cases; the data window size affects the detection time of abnormal and unbalance conditions,
3. The severity degrees of voltage/current can be assessed, for all possible contingencies and unbalances, using the alienation coefficients; thus, the developed method is a useful tool in mitigation techniques applied to compensate voltage and current unbalance effects in power systems,
4. It is characterized by being accurate, reliable and robust; and it can be applied in generation, transmission, distribution and utilization systems with various voltage levels, besides it can be a crucial solution of unbalance detection and assessment for traditional, smart grids and digital substations,
5. Its sensitivity and security can be controlled via selecting the alienation/coherence deviation settings and the size of the coherent data window,
6. The setting values of alienation can be adaptive based on the prevailed conditions of power grids and the acceptable unbalance for voltage and current signals,
7. The approach develops new closed and quadratic-tripping characteristics based on alienation/coherence limits,
8. It is independent on the parameters data of power system elements and instrument transformers (such as voltage and current transformers),
9. The proposed algorithm can be a base for digital fault recorders, protective relays, besides voltage and current disturbances detectors, and
10. It could be used in adaptive protection relays and systems to make adaptation of tripping characteristics (such as differential overcurrent relays and voltage-controlled time overcurrent relays).

Table 5 presents a comparison between the proposed protection scheme and the other conventional backup protection methods. This comparison describes the effectiveness of the developed scheme from various viewpoints, such as tripping characteristics, pre-setting values, speed, reliability, security, sensitivity, simplicity, multi-functions, low pass filter, and so on.

6 | CONCLUSIONS

The proposed technique is considered as an adaptive backup relay, against the disturbances of power quality parameters, used to protect the synchronous generator which is one of the important elements of the power system. The power quality parameters represent variations of frequency, amplitude, waveform shape, and symmetry. The tripping time of the algorithm is set to be at least one cycle to assure that the main protective relay has failed to operate. This tripping time depends on the severity degree of unbalance or disturbance in the three-phase voltage and current signals which gives the adaptive action to the suggested algorithm. The tripping action is based on 15 alienation coefficients derived from the coherence coefficients for these phase voltage and current signals. Extensive experimental investigations have been implemented and evaluated using the alienation-based protection algorithm. The developed algorithm has been proven that it is fast, stable, robust, adaptive, accurate (95.83%), dependable (97.62%), secure (96.47%) and reliable (94.25%). It can be applied in generation, transmission, distribution and utilization systems with various voltage levels for traditional, smart grids and digital substations. The superiority of this approach is the determination of the various series and shunt fault and unbalance conditions utilizing the proposed closed-tripping characteristics dependent on the alienation boundary. Moreover, it is able to modify the alienation threshold settings to control the sensitivity and security of the proposed relay.
TABLE 5 compares between the proposed technique and the conventional methods of backup relays

| Item of comparison            | Alienation/coherence-based proposed protection scheme                                                                 | The conventional backup relays for synchronous generators                                                                 |
|-------------------------------|--------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| 1. Selected setting values    | - Only one setting value, for alienation/coherence coefficients, can be selected for all variables. 
                          | - It can select the most suitable operating setting of the alienation/coherence factor (adaptive setting) according to the prevailed conditions of a power system. | - They select various settings for voltage/current magnitude, phase shift and time delay.                                |
| 2. Tripping characteristics   | - The method develops new closed-tripping characteristics, which are based on alienation/coherence coefficients with restricted values between the two values of ‘0’ and ‘+1’ that are similar to per unit magnitudes. | - Most of them have open tripping characteristics, which are without restriction values for voltage and/or current variables, even though they are in per unit values. This is except the tripping characteristic of the impedance relay that functions as a backup protection for synchronous generator. |
| 3. Operating time delay       | - The operating time delay is controllable using the suitable data window size, and it can be chosen to be less than one cycle (i.e. sub cycle), if the algorithm selects a sub-cycle of the data window, this accelerates relay operation. | - The operating time delay is greater than one cycle because some of the conventional methods depend on calculating the RMS values of voltage and/or current, which requires at least a period of one cycle. |
| (relay speed)                 | - The proposed technique can be used to carry out various protection functions such as: 
                          | ○ Voltage and current disturbance detector, 
                          | ○ Voltage and current unbalance detector, 
                          | ○ Assessment of voltage and current unbalance, and 
                          | ○ Assessment of voltage and current disturbance, 
                          | - Moreover, it can be used as a base for digital synchro-check relay, and power factor meter/relay. | - Some of them perform only one protection function in the protective relay. 
                          | - Other relays carry out a variety of protection algorithms to perform multi-functions protection, which require different types of mathematical formulas. |
| 4. Multi-algorithms and       | - The proposed novel protection scheme requires no data synchronization system. 
                          | - Most of them require no data synchronization system when transmitting data. | - Some of them are complex, accurate, dependable, secure, reliable, sensitive, and stable system. 
                          | multi-functions | - It is simple, accurate, dependable, secure, reliable, sensitive, and stable system. | - Some of them are complex systems because they are difficult while maintenance and installation. |
|                              | - It is simple in maintenance, installation and operation. The simpler the protection system it will more reliable. | - It is simple system in maintenance, installation and operation. The simpler the protection system it will more reliable. | - It is simple system in maintenance, installation and operation. The simpler the protection system it will more reliable. |
| 5. Data synchronization       | - The proposed technique can be used to carry out various protection functions such as: 
                          | - Need DAC (Data Acquisition Card) to convert the analog signals to the digital signals. 
                          | - Need software for processing the DAC. | - Some of them are complex, accurate, dependable, secure, reliable, sensitive, and stable system. 
                          | system          | - Need software for processing the DAC. | - Some of them are complex, accurate, dependable, secure, reliable, sensitive, and stable system. |
|                              | - The proposed technique can be used to carry out various protection functions such as: 
                          | - Need software for processing the DAC. | - Some of them are complex, accurate, dependable, secure, reliable, sensitive, and stable system. 
                          |                              | - The selected data window size, used in calculation of alienation/coherence factors, is considered as a digital low pass filter. | - Some of them require an additional digital low pass filter. In the case of harmonic distortion, the Fourier Transform filters harmonics, and therefore it is recommended to use it to calculate the Root Mean Square (RMS) value. |
| 6. Relay properties           | - The proposed technique can be used to carry out various protection functions such as: 
                          | - Need DAC (Data Acquisition Card) to convert the analog signals to the digital signals. 
                          | - Need software for processing the DAC. | - Some of them require an additional digital low pass filter. In the case of harmonic distortion, the Fourier Transform filters harmonics, and therefore it is recommended to use it to calculate the Root Mean Square (RMS) value. |
| 7. Criteria simplicity        | - The proposed technique can be used to carry out various protection functions such as: 
                          | - Need DAC (Data Acquisition Card) to convert the analog signals to the digital signals. 
                          | - Need software for processing the DAC. | - Some of them require an additional digital low pass filter. In the case of harmonic distortion, the Fourier Transform filters harmonics, and therefore it is recommended to use it to calculate the Root Mean Square (RMS) value. |
|                              | - The proposed technique can be used to carry out various protection functions such as: 
                          | - Need DAC (Data Acquisition Card) to convert the analog signals to the digital signals. 
                          | - Need software for processing the DAC. | - Some of them require an additional digital low pass filter. In the case of harmonic distortion, the Fourier Transform filters harmonics, and therefore it is recommended to use it to calculate the Root Mean Square (RMS) value. |
| 8. Cost of implementation     | - The proposed technique can be used to carry out various protection functions such as: 
                          | - Need DAC (Data Acquisition Card) to convert the analog signals to the digital signals. 
                          | - Need software for processing the DAC. | - Some of them require an additional digital low pass filter. In the case of harmonic distortion, the Fourier Transform filters harmonics, and therefore it is recommended to use it to calculate the Root Mean Square (RMS) value. |
|                              | - The proposed technique can be used to carry out various protection functions such as: 
                          | - Need DAC (Data Acquisition Card) to convert the analog signals to the digital signals. 
                          | - Need software for processing the DAC. | - Some of them require an additional digital low pass filter. In the case of harmonic distortion, the Fourier Transform filters harmonics, and therefore it is recommended to use it to calculate the Root Mean Square (RMS) value. |
| 9. Digital low pass filter    | - The proposed technique can be used to carry out various protection functions such as: 
                          | - Need DAC (Data Acquisition Card) to convert the analog signals to the digital signals. 
                          | - Need software for processing the DAC. | - Some of them require an additional digital low pass filter. In the case of harmonic distortion, the Fourier Transform filters harmonics, and therefore it is recommended to use it to calculate the Root Mean Square (RMS) value. |
| 10. CT saturation detection   | - The proposed technique can be used to carry out various protection functions such as: 
                          | - Need DAC (Data Acquisition Card) to convert the analog signals to the digital signals. 
                          | - Need software for processing the DAC. | - Some of them require an additional digital low pass filter. In the case of harmonic distortion, the Fourier Transform filters harmonics, and therefore it is recommended to use it to calculate the Root Mean Square (RMS) value. |

NOMENCLATURE

\(3LN\) Three line-to-neutral fault,
\(Ai_{ab}\) The auto-alienation coefficient calculated between the two successive data windows of phase voltage signal \(i_a(n)\) and \(i_b(n-N_s)\) for the phase ‘A’,
\(Ai_{bc}\) The cross-alienation coefficient calculated between the two current signals \(i_a(n)\) and \(i_c(n)\),
\(Ai_{bc}\) The auto-alienation coefficient calculated between the two successive data windows

\(Ai_{ab}\) The auto-alienation coefficient calculated between the two successive data windows of phase voltage signal \(i_a(n)\) and \(i_b(n-N_s)\) for the phase ‘B’,
\(Ai_{bc}\) The cross-alienation coefficient calculated between the two current signals \(i_a(n)\) and \(i_b(n-N_s)\) for the phase ‘B’,
\(Ai_{bc}\) The cross-alienation coefficient calculated between the two current signals \(i_a(n)\) and \(i_c(n)\),
\(Ai_{bc}\) The auto-alienation coefficient calculated between the two successive data windows
of phase voltage signal \((i_c(n)\) and \(i_c(n-N_s)\))

\[A_{i_{ca}}\] The cross-alienation coefficient calculated between the two current signals \((i_a(n)\) and \(i_a(n-N_s)\))

\[A_{i_{ia}}\] The auto-alienation coefficient calculated between the two successive data windows of phase voltage signal \((i_a(n)\) and \(i_a(n-N_s)\)) for the phase ‘C’.

\[A_{i_{ic}}\] The cross-alienation coefficient calculated between the two current signals \((i_a(n)\) and \(i_c(n-N_s)\))

\[A_{i_{ia}}\] The auto-alienation coefficient calculated between the two successive data windows of phase voltage signal \((i_a(n)\) and \(i_a(n-N_s)\)) for the phase ‘S’.

\[A_{i_{ic}}\] The cross-alienation coefficient calculated between the two current signals \((i_a(n)\) and \(i_c(n-N_s)\))

\[A_{i_{ia}}\] The auto-alienation coefficient calculated between the two successive data windows of phase voltage signal \((i_a(n)\) and \(i_a(n-N_s)\)) for the phase ‘A’.

\[A_{i_{ib}}\] The cross-alienation coefficient calculated between the two voltage signals \((v_b(n)\) and \(v_b(n-N_s)\))

\[A_{i_{ib}}\] The auto-alienation coefficient calculated between the two successive data windows of phase voltage signal \((v_b(n)\) and \(v_b(n-N_s)\)) for the phase ‘B’.

\[A_{i_{ic}}\] The cross-alienation coefficient calculated between the two voltage signals \((v_c(n)\) and \(v_c(n-N_s)\)) for the phase ‘C’.

\[A_{i_{ic}}\] The cross-alienation coefficient calculated between the two voltage signals \((v_c(n)\) and \(v_c(n-N_s)\)) for the phase ‘A’.

\[A_{i_{ic}}\] The cross-alienation coefficient calculated between the two voltage signals \((v_c(n)\) and \(v_c(n-N_s)\)) for the phase ‘B’.

\[A_{i_{ia}}\] The auto-alienation coefficient calculated between the two successive data windows of phase voltage signal \((v_c(n)\) and \(v_c(n-N_s)\)) for the phase ‘C’.

\[A_{i_{ib}}\] The cross-alienation coefficient calculated between the two voltage signals \((v_b(n)\) and \(v_b(n-N_s)\)) for the phase ‘B’.

\[A_{i_{ic}}\] The cross-alienation coefficient calculated between the two voltage signals \((v_c(n)\) and \(v_c(n-N_s)\)) for the phase ‘C’.

\[C_{i_{ab}}(k)\] The cross-coherence coefficient calculated between the two current signals \((i_a(n)\) and \(i_b(n-N_s)\))

\[C_{i_{bc}}(k)\] The auto-coherence coefficient, on a given frequency \((k)\), calculated between each two successive data windows shifted from each other by one-cycle interval of the current signal \((i_a(n)\) and \(i_a(n-N_s)\)) of the ‘A’ phase.

\[C_{i_{bc}}(k)\] The cross-coherence coefficient calculated between the two current signals \((i_b(n)\) and \(i_b(n-N_s)\))

\[C_{i_{bc}}(k)\] The auto-coherence coefficient, on a given frequency \((k)\), calculated between each two successive data windows shifted from each other by one-cycle interval of the current signal \((i_b(n)\) and \(i_b(n-N_s)\)) of the ‘B’ phase.

\[C_{i_{bc}}(k)\] The cross-coherence coefficient calculated between the two current signals \((i_c(n)\) and \(i_c(n-N_s)\))

\[C_{i_{bc}}(k)\] The auto-coherence coefficient, on a given frequency \((k)\), calculated between each two successive data windows shifted from each other by one-cycle interval of the current signal \((i_c(n)\) and \(i_c(n-N_s)\)) of the ‘C’ phase.

\[C_{i_{bc}}(k)\] The cross-coherence coefficient calculated between the two sampled current signals \((i_a(n)\) and \(i_b(n-N_s)\)) for the two different phases ‘A’ and ‘B’, respectively, on a given frequency \((k)\); the coefficient is a real value.

\[C{T1, C{T2, C{T3, C{T4 AND C{T5}}}}\] Current Transformers no. 1, 2, 3, 4 and 5

\[C{T}R\] Current Transformer Ratio,

\[C{r_{ab}}(k)\] The auto-coherence coefficient, on a given frequency \((k)\), calculated between each two successive data windows shifted from each other by one-cycle interval of the voltage signal \((v_a(n)\) and \(v_a(n-N_s)\)) of the ‘A’ phase.

\[C{r_{bc}}(k)\] The cross-coherence coefficient calculated between the two voltage signals \((v_a(n)\) and \(v_b(n-N_s)\))

\[C{r_{bc}}(k)\] The auto-coherence coefficient, on a given frequency \((k)\), calculated between each two successive data windows shifted from each other by one-cycle interval of the voltage signal \((v_a(n)\) and \(v_b(n-N_s)\)) of the ‘B’ phase.

\[C{r_{bc}}(k)\] The cross-coherence coefficient calculated between the two voltage signals \((v_b(n)\) and \(v_b(n-N_s)\))

\[C{r_{bc}}(k)\] The auto-coherence coefficient, on a given frequency \((k)\), calculated between each two successive data windows shifted from each other by one-cycle interval of the voltage signal \((v_a(n)\) and \(v_b(n-N_s)\)) of the ‘C’ phase.
\( \text{Cvi}_a(k) \) The cross-coherence coefficient calculated between the two voltage signals \((v_a(n)\) and \(v_b(n))\),

\( \text{Cvi}_b(k) \) The cross-coherence coefficient calculated between the phase voltage and current signals \((v_a(n)\) and \(i_a(n))\),

\( \text{Cvi}_c(k) \) The cross-coherence coefficient calculated between the phase voltage and current signals \((v_b(n)\) and \(i_b(n))\),

\( \text{Cvi}_d(k) \) The cross-coherence coefficient calculated between the phase voltage and current signals \((v_c(n)\) and \(i_c(n))\),

\( \text{Cvii}(k) \) The auto-coherence coefficient, on a given frequency \(k\); the coefficient is a real value,

\( \text{Cvi}(k) \) The cross-coherence coefficient, on a given frequency \(k\), calculated between each two successive data windows shifted from each other by one-cycle interval of the voltage signal \((v_a(n)\) and \(v_a(n-Ns))\) of the \(S\) phase,

\( \text{Cvi}_{\alpha}(k) \) The cross-coherence coefficient calculated between the two sampled voltage signals \((v_a(n)\) and \(v_a(n))\) for the two phases \(S\) and \(X\), respectively, on a given frequency \(k\); the coefficient is a real value,

\( DL \) Double line fault,

\( DLN \) Double line-to-neutral fault,

\( F_s \) The fundamental frequency of one periodic cycle, \((F_s = 50\text{ Hz})\),

\( F_s \) The sampling frequency, \((F_s = 2.5\text{ kHz})\),

\( i_a(n), i_b(n) \) and \( i_c(n) \) The three phase instantaneous values of current signals at sample \(n\) measured at the SG terminals, of phases for phases \(A\), \(B\) and \(C\), respectively,

\( I_s \) The nominal current of the synchronous generator,

\( i_a(n-Ns) \) The instantaneous phase current signal \(i_a(n)\) at sample one-cycle prior to \(n\) of \(S\) phase,

\( i_a(n) \) The instantaneous current signal for every sample \(n\) of phase \(S\); \(n = 0, 1, \ldots(N-1)\),

\( I_{s1}(k) \) Cosine coefficient of the DFT for phase current signal \(i_a(n)\),

\( I_{s2}(k) \) Sine coefficient of the DFT for phase current signal \(i_a(n)\),

\( I_{s3}(k) \) Cosine coefficient of the DFT for phase current signal \(i_a(n-Ns)\),

\( I_{s4}(k) \) Sine coefficient of the DFT for phase current signal \(i_a(n-Ns)\),

\( i_a(n) \) The instantaneous current signal for every sample \(n\) of phase \(X\); \(n = 0, 1, \ldots(N-1)\),

\( I_{s1}(k) \) Cosine coefficient of the DFT for phase current signal \(i_a(n)\),

\( I_{s2}(k) \) Sine coefficient of the DFT for phase current signal \(i_a(n)\),

\( K \) The \(k\)th frequency component; \(k = 0, 1, \ldots(N-1)\),

\( MCB MCB_1, MCB_2, MCB_3, MCB_4 \) and \( MCB_5 \) miniature circuit breaker, and miniature circuit breaker no. 1, 2, 3, 4 and 5,

\( N \) The \(n\)th sample (in the time domain), \(n = 0, 1, \ldots(N-1)\),

\( N \) The number of samples per window used in the technique \((N \leq N_s)\),

\( N_i \) The number of samples per cycle for each voltage signal \((v_a(n)\) and \(v_a(n))\), \((N_i = T_f \times F_s / F_r)\) and \(N_i = 50\) Samples/cycle,

\( N_f \) The full samples per the display time,

\( PF \) Power factor,

\( R_f \) The current resistance imposed from the faulted point on SG terminal to the neutral point in case of the ground fault or inserted between the two faulted phases in case of the fault phase,

\( R_{lead} \) The lead resistance connected between the current transformer terminals and the burden,

\( RMS \) The Root Mean Square,

\( R_g \) Generator grounding impedance through the neutral point,

\( S \) and \( X \) The phase designation \(A\), \(B\) or \(C\); but they are not the same phase,

\( SG \) Synchronous Generator,

\( SLD \) Single line diagram,

\( SLN \) Single line-to-neutral fault,

\( T_f \) The cycle time period, \((T_f = 20\text{ mSec})\),

\( T_s \) The sampling time interval, \((T_s = 0.4\text{ mSec})\),

\( v_a(n), v_b(n) \) The three phase instantaneous values of voltage signals at sample \(n\) measured at the SG terminals for phases \(A\), \(B\) and \(C\), respectively,

\( V_g \) The nominal voltage of the synchronous generator,

\( v_a(n-Ns) \) The instantaneous phase voltage signal \(v_a(n)\) at sample one-cycle prior to \(n\) of \(S\) phase,

\( v_a(n) \) The instantaneous voltage signal for every sample \(n\) of phase \(S\); \(n = 0, 1, \ldots(N-1)\),

\( V_{s1}(k) \) Cosine coefficient of the DFT for phase voltage signal \(v_a(n)\),

\( V_{s2}(k) \) Sine coefficient of the DFT for phase voltage signal \(v_a(n)\),

\( V_{s3}(k) \) Cosine coefficient of the DFT for phase voltage signal \(v_a(n-Ns)\),

\( V_{s4}(k) \) Sine coefficient of the DFT for phase voltage signal \(v_a(n-Ns)\),

\( VT \) Voltage Transformer,

\( VT_1, VT_2 \) Voltage Transformers no. 1, 2 and 3,

\( VTR \) Voltage Transformer Ratio,
\( v_x(n) \) The instantaneous voltage signal for every sample \( n \) of phase \( X \), \( n = 0, 1, \ldots (N-1) \).

\( V_{x1}(k) \) Cosine coefficient of the DFT for phase voltage signal \( v_x(n) \).

\( V_{x2}(k) \) Sine coefficient of the DFT for phase voltage signal \( v_x(n) \).

\( \Delta u \) and \( \Delta w \) The auto-alienation setting deviations; they lie between the values 0.0 and 0.25.

\( \Delta x \) and \( \Delta y \) and \( \Delta z \) The cross-alienation setting deviations; \( \Delta x \) and \( \Delta y \) lie between the values 0.0 and 0.25.

\( \Delta \xi \) The cross-alienation setting deviation \( \Delta \xi \) lies between the values of 0.0 and 0.75, it depends on the acceptable power factor

\( \Omega \) The angular velocity of the power system (\( \omega = 2 \pi f \)).

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