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Unbalance Current Detection for Synchronous Generator Using Alienation Concept

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Abstract— ***In modern digital power protection systems, statistical coefficients technique is recently used for fault analysis. An alienation technique is developed for protecting synchronous generators against unbalance currents conditions. The proposed technique is able to accurately identify the conditions of unbalance phase(s) currents involved in all different types of shunt faults that may locate on stator windings of synchronous generator. Case studies are processed under different loading levels, fault resistances and fault inception angles. It does not need any extra equipment as it depends only on the three-line currents measurements which are mostly available at the relay location. This technique is able to detect the unbalance current conditions, in about a one-cycle period. Thus, the alienation technique is well suited for implementation in digital protection schemes. The proposed methodology is applied for El-kuriemat power station unit that produces 320 MVA and a part of 500 KV Egyptian network. Alternative transient program (ATP) and MATLAB programs are used to implement the proposed technique.***

Index Terms— ***Generator protection, unbalance currents, alienation coefficient, internal and external fault..***

I. INTRODUCTION

Synchronous generator is the core of electrical power system; once it is defected the network cannot continue working properly. Many types of faults will be occurring in the power system and on the generator itself. So, there is a necessity to protect the generator from those faults to limit the possible damage; hence generator protection has dual protection objectives. All faults associated with synchronous generators may be classified as either insulation failures or abnormal running conditions [1-2]. An insulation failure in the stator winding will result in an inter-turn fault, a phase fault or a ground fault, but most commonly the latter since most insulation failures eventually bring the winding into direct contact with the core [1]. Differential relays, in particular the digital ones, are used as a main (primary) protection to detect stator faults of generators. Electric power utilities and industrial plants traditionally use electromechanical and solid-state relays for protecting synchronous generators. With the advent of digital technology, researchers and designers have made significant progress in developing protection systems based on digital and microprocessor techniques. Sachdev and Wind [3-4] developed an algorithm that uses instantaneous differences between line and neutral end currents for detecting phase faults. Negative sequence relays (NSR) are commonly used in power system as backup (secondary) protection, Particularly for detecting faulty conditions. NSR are based on negative sequence components. Negative and zero-sequence components are present in relatively large values under unbalance or faulty conditions. Negative-sequence components are used to detect phase-to-phase, phase-to-ground, and double line-to-ground faults. However Zero-sequence components are used to detect phase-to-ground and double phase-to-ground faults [5]. The advantage of the negative sequence current (NSC) components over zero sequence current (ZSC) component is that, mutually coupled parallel line currents does not influencing the measurement and only the three phase currents are used as inputs (the neutral current is not needed) [6]. NSR are used in different application of power system. For example: To detect unbalance loading on generator which may cause excessive heating in the rotor, unbalanced current in motors which may cause intolerable vibration in the motor, sometimes also used in transmission systems to detect unbalanced conditions and asymmetrical faults[6]. The unbalance system is not very useful from protection perspective. Unbalanced currents give rise to a negative sequence component in the stator current of the generator. The NSC produces an additional counter flux which rotates at synchronous speed in the opposite direction of the rotor. The eddy currents which are induced in the rotor parts double the network frequency currents, which result in the high temperature rise of the rotor and cause the mechanical stress on the rotating components [6]. An on-line digital computer technique for protection of a generator against internal asymmetrical faults is described by P. K. Dash and O. P. Malik [7-8] in which the discrimination against external faults is achieved by monitoring the direction of the negative sequence power flow at the machine terminals. A digital relay for generator protection against asymmetrical faults is presented in [9]. Under unbalanced conditions, the three-phase instantaneous power oscillates at twice the power system frequency. The magnitude of these oscillations can be used as a measurement of the system unbalance; the paper in [9] introduced a new digital relay algorithm designed to detect asymmetrical faults by monitoring the sinusoidal oscillations of the three-phase instantaneous power measured at the generator terminals. Once an asymmetrical fault is detected, the algorithm checks the direction of the negative sequence reactive power flowing at the machine terminals to discriminate between the internal and external faults. The author in [10] has analyzed the effects of NSC on generator rotors. According to the standard IEC 60034-1 turbine generators must be designed for unbalanced load. It must have capability to tolerate a permanent NSC of up to 10% of the rated current.

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Most of the manufacturers guaranty the negative sequence capability of their generators by experience. The paper in [10] has also presented the new method for the determination of NSC. The author in [11] has analyzed the operation of NSR in distribution system and has shown that the relay can be set faster and more sensitively than phase over-current relay (OCR) for phase-to-phase faults. However NSR should be properly coordinated with OCR for reliable operation of power system. The author has also set up some guide lines for proper coordination. The paper in [12] has presented the design and various data conversion steps of a digital negative sequence relay. The modeling of the digital negative sequence relays is processed using MATLAB/SIMULINK. As compared to other power relays model in existing power system softwares, MATLAB offers advantage in terms of their flexibility. The last paper showed that the digital relay has a superiority over electromechanical relay in terms of accuracy and speed, the detection of negative sequence current and appropriate action is useful for protection of power system components and the operation of relay should be fast and reliable for minimum outage of power system in case of abnormality or electrical fault. The negative sequence relay can also be used in the other applications such as: (1) Phase interruptions (e.g. a broken conductor), (2) Failure on one or two poles of a circuit breaker or disconnect switch at opening and closing, (3) Earth-fault detection in solidly earthed system and (4) A short circuit between two-phases will give a large negative sequence current, but these faults are normally cleared by the short circuit (main) protection in much shorter time than the operate time of the NSR. This paper proposes unbalance current protection algorithm based on alienation technique for synchronous generator. The technique measures the three-phase currents at stator winding terminals. The alienation coefficients are calculated between each two phase currents for protecting synchronous generator against unbalance current conditions and making relay trip or no trip decision. The suggested technique can operate accurately during one-cycle period of the fundamental frequency. Also, this technique takes into consideration the wide variations of operating conditions such as loading levels, fault resistances and fault inception angles.

II. Proposed Technique

A. Basic Principles

In this paper, ATP software [13] is used to get reliable simulation results before and during different fault conditions which cause unbalance currents at the three terminals of stator windings for synchronous generator. Three-phase current measurements are sufficient to implement our technique. Three single current transformers (CTA, CTB and CTC) are built to get low current signals in high voltage system. Three-phase current signals (i_a, i_b and i_c) are obtained and stored in a file; this data is in the discrete sampled form. These current samples are processed in MATLAB to estimate alienation coefficients [14-15] between each two phase current signals. The algorithm processes the calculations of the alienation coefficients for each two corresponding cycles of each two phase current signals measured at the relay location. The suggested technique is based on alienation concept in order to determine the condition of power system is whether balance or unbalance currents.

B. Alienation Coefficients Calculation

The variance between any two signals is defined as the alienation coefficient [16-18]; it is derived from correlation coefficient. Cross-correlation coefficient detects any phase difference between any two electrical signals in power system; thus alienation coefficient is a good tool to propose a technique for making unbalance current protection against abnormal current conditions. Alienation coefficient calculated between each two phase current signals can recognize a phase shift between them and to operate in response to it. Cross-correlation coefficient (r_{ab}) is calculated between two windows in two sampled current signals (i_a and i_b) obtained from two phase current transformers (CTA, CTB), where the two windows are shifted from each other with a time interval $h\Delta t$. The cross-correlation coefficient of two signals (i_a and i_b) is given by Equation (1). Our proposed technique uses the two signals shifted from each other when the time interval $h\Delta t = 0$, where $h = 0$ (h is the number of samples between the two windows which are shifted from each other and Δt is the time interval of one sample). Also cross-correlation coefficients (r_{bc} *and* r_{ca}) are given by Equations (2) and (3), respectively.

$$r_{ab}=\frac{\sum_{k=1}^{m} i_a(k)i_b(k+h\Delta t)-\frac{1}{m}\sum_{k=1}^{m} i_a(k)\sum_{k=1}^{m} i_b(k+h\Delta t)}{\left(\sqrt{\sum_{k=1}^{m}(i_a(k))^2-\frac{1}{m}\left(\sum_{k=1}^{m} i_a(k)\right)^2}\right)\times\left(\sqrt{\sum_{k=1}^{m}(i_b(k+h\Delta t))^2-\frac{1}{m}\left(\sum_{k=1}^{m} i_b(k+h\Delta t)\right)^2}\right)} \quad (1)$$

$$r_{bc}=\frac{\sum_{k=1}^{m} i_b(k)i_c(k+h\Delta t)-\frac{1}{m}\sum_{k=1}^{m} i_b(k)\sum_{k=1}^{m} i_c(k+h\Delta t)}{\left(\sqrt{\sum_{k=1}^{m}(i_b(k))^2-\frac{1}{m}\left(\sum_{k=1}^{m} i_b(k)\right)^2}\right)\times\left(\sqrt{\sum_{k=1}^{m}(i_c(k+h\Delta t))^2-\frac{1}{m}\left(\sum_{k=1}^{m} i_c(k+h\Delta t)\right)^2}\right)} \quad (2)$$

$$r_{ca}=\frac{\sum_{k=1}^{m} i_c(k)i_a(k+h\Delta t)-\frac{1}{m}\sum_{k=1}^{m} i_c(k)\sum_{k=1}^{m} i_a(k+h\Delta t)}{\left(\sqrt{\sum_{k=1}^{m}(i_c(k))^2-\frac{1}{m}\left(\sum_{k=1}^{m} i_c(k)\right)^2}\right)\times\left(\sqrt{\sum_{k=1}^{m}(i_a(k+h\Delta t))^2-\frac{1}{m}\left(\sum_{k=1}^{m} i_a(k+h\Delta t)\right)^2}\right)} \quad (3)$$

Where,

r_{ab} = The cross-correlation coefficient calculated between the two secondary current signals (i_a and i_b).

r_{bc} = The cross-correlation coefficient calculated between the two secondary current signals (i_b and i_c).

r_{ca} = The cross-correlation coefficient calculated between the two secondary current signals (i_c and i_a).

m: the number of samples per window to be correlated used in the algorithm (the number of samples per cycle are selected in the algorithm, $m = N = 100$ samples).

N: the number of samples per cycle.

i_a *(k):* the sampled secondary current values at instant k measured from CTA at stator windings terminal of phase ‘‘*A*’’.

i_b *(k):* the sampled secondary current values at instant k measured from CTB at stator windings terminal of phase ‘‘*B*’’.

i_c *(k):* the sampled secondary current values at instant k measured from CTC at stator windings terminal of phase ‘‘*C*’’.

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The alienation coefficient (A_{ab}) calculated between the two secondary current signals (i_a and i_b) is obtained from cross-correlation coefficient (r_{ab}) and given by Equation (4). Also alienation coefficients (A_{bc} and A_{ca}) are given by Equations (5) and (6), respectively.

$$A_{ab} = 1 - (r_{ab})^2 \quad (4)$$

$$A_{bc} = 1 - (r_{bc})^2 \quad (5)$$

$$A_{ca} = 1 - (r_{ca})^2 \quad (6)$$

Where,

A_{ab} = The alienation coefficient calculated between the two secondary current signals (i_a and i_b).

A_{bc} = The alienation coefficient calculated between the two secondary current signals (i_b and i_c).

A_{ca} = The alienation coefficient calculated between the two secondary current signals (i_c and i_a).

Cross-correlation coefficient is considered as the cosine of the phase angle between any two current signals. Correlation and alienation coefficients are a dimensionless quantities and it does not depend on the units employed. The value of cross-correlation is between "-1" and "1", this produces the value of alienation coefficient to be between "0" and "1".

C. Unbalance Current Detection Procedures

Flow chart for unbalance current protection algorithm based on alienation technique is shown in Fig. (1). The algorithm has the following procedures:

1- Read discrete samples of three-phase secondary current signals (i_a, i_b and i_c) for three-phase current transformers (CTA, CTB and CTC, respectively) located at load side of synchronous generator (obtained from ATP tool).

2- Calculate cross-correlation coefficients (r_{ab}, r_{bc} and r_{ca}) as given by Equations (7), (8) and (9), respectively.

$$r_{ab} = \frac{\sum_{k=1}^{m} i_a(k) i_b(k) - \frac{1}{m}\sum_{k=1}^{m} i_a(k) \sum_{k=1}^{m} i_b(k)}{\left(\sqrt{\sum_{k=1}^{m}(i_a(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_a(k))^2}\right) \times \left(\sqrt{\sum_{k=1}^{m}(i_b(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_b(k))^2}\right)} \quad (7)$$

$$r_{bc} = \frac{\sum_{k=1}^{m} i_b(k) i_c(k) - \frac{1}{m}\sum_{k=1}^{m} i_b(k) \sum_{k=1}^{m} i_c(k)}{\left(\sqrt{\sum_{k=1}^{m}(i_b(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_b(k))^2}\right) \times \left(\sqrt{\sum_{k=1}^{m}(i_c(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_c(k))^2}\right)} \quad (8)$$

$$r_{ca} = \frac{\sum_{k=1}^{m} i_c(k) i_a(k) - \frac{1}{m}\sum_{k=1}^{m} i_c(k) \sum_{k=1}^{m} i_a(k)}{\left(\sqrt{\sum_{k=1}^{m}(i_c(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_c(k))^2}\right) \times \left(\sqrt{\sum_{k=1}^{m}(i_a(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_a(k))^2}\right)} \quad (9)$$

The three cross-correlation coefficients (r_{ab}, r_{bc} and r_{ca}) indicate to the cosine phase shift between each two phase currents Φ_{ab}, Φ_{bc} and Φ_{ca}, respectively.

Φ_{ab} = $\text{Cos}^{-1}(r_{ab})$, (where, $Cos(\Phi_{ab})$ = the cosine of the phase angle between the two secondary current signals of the two current transformers (CTA and CTB).

Φ_{bc} = $\text{Cos}^{-1}(r_{bc})$, (where, $Cos(\Phi_{bc})$ = the cosine of the phase angle between the two secondary current signals of the two current transformers (CTB and CTC).

Φ_{ca} = $\text{Cos}^{-1}(r_{ca})$, (where, $Cos(\Phi_{ca})$ = the cosine of the phase angle between the two secondary current signals of the two current transformers (CTC and CTA).

3- Calculate the alienation coefficients (A_{ab}, A_{bc} and A_{ca}), by using the calculated cross-correlation coefficients (r_{ab}, r_{bc} and r_{ca}, respectively) as estimated in Equations (4), (5) and (6).

It is known that the unbalanced load condition causes unbalanced phase angle shifts for three-phase currents of generators. This rule is used for comparison the phase angle differences between each two secondary currents of the three-phase current transformers built at load side. This is performed by the calculations of alienation coefficients between each two current signals. These coefficients give an indication for the asymmetrical current loads.

During normal operation, the value of cross-correlation coefficient is - 0.5 because the phase shift is 120^0 in case of ideal balanced operation ($r_{ab} = r_{bc} = r_{ca} = Cos\ (120^o) = -0.5$), hence the corresponding alienation coefficients ($A_{ab} = A_{bc} = A_{ca} = 1- (Cos\ (120^o))^2 = 0.75$). Whereas in case of unbalanced loading, ($r_{ab} \neq r_{bc} \neq r_{ca} \neq cos(120^o) \neq -0.5$), hence, ($A_{ab} \neq A_{bc} \neq A_{ca} \neq 1- (Cos\ (120^o))^2 \neq 0.75$).

Fig. (2) shows the proposed tripping characteristic of the suggested technique of unbalance currents protection function. The relay characteristics shows that the ideal balance gives alienation coefficient (A_{ab}, A_{bc} or A_{ca}) value = 0.75, but no ideal balance operation with generator loading. To avoid this drawback, the operation under balance condition is limited by two alienation coefficients (A_x and A_y).

Where,

$A_x = [1- (Cos(120 - |\Delta\varphi|))^2]$,

$A_y = [1- (Cos(120 + |\Delta\varphi|))^2]$ and

$\Delta\varphi$ = The maximum acceptable value of angle phase shift (in degree) over ideal angle level and it has a value from -30 Degree to 30 Degree with step 1 Degree). In our proposed algorithm, the selected threshold value of unbalanced shift angle ($\Delta\varphi$) = 5 Degree, A_x = 0.67 and A_y = 0.82.

4- Tripping/blocking action of the algorithm relies on the following rules:

<u>(a) Balance current condition</u>

The following conditions must be verified for balance currents:

- If $A_x < A_{ab} < A_y$, $A_x < A_{bc} < A_y$ and $A_x < A_{ca} < A_y$ (for each two phases currents), then this case is normal operation condition with acceptable balanced currents, where, A_x = 0.67 and A_y = 0.82 are selected.
- $A_{ab} \approx A_{bc} \approx A_{ca}$

<u>(b) Unbalance current condition</u>

The following conditions must be verified for moderate unbalance currents:

- If ($A_{x1} \le A_{ab} \le A_x$ or $A_y \le A_{ab} \le A_{y1}$), ($A_{x1} \le A_{bc} \le A_x$ or $A_y \le A_{bc} \le A_{y1}$) or ($A_{x1} \le A_{ca} \le A_x$ or $A_y \le A_{ca} \le A_{y1}$), where, A_{x1} = 0.59 and A_{y1} = 0.88. (for any two phases currents), then this case indicates to moderate unbalance currents condition and it is required operation of cooling system for the protected generator.
- $A_{ab} \neq A_{bc} \neq A_{ca}$

<u>(c) Severe unbalance current condition</u>

The following conditions must be verified for severe unbalance currents:

- If $A_{x1} > A_{ab} > A_{y1}$, $A_{x1} > A_{bc} > A_{y1}$ or $A_{x1} > A_{ca} > A_{y1}$ (for any two phases currents), then this case indicates to severe unbalance currents condition and it is required tripping for generator CB.

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- $A_{ab} \neq A_{bc} \neq A_{ca}$

- $T_u = T_{definite}$, *where*, T_u = Operating time (in Sec) of unbalance currents protection function.

The three types of unbalance current conditions are given in Table (1). In our proposed technique, the cooling system for stator windings should be the first line of defense against unbalance currents. The technique sends a trip signal for generator circuit breaker once severe unbalance currents events are satisfied. The unbalance currents protection algorithm is considered as backup (secondary) protection besides the main (primary) protection of synchronous generator.

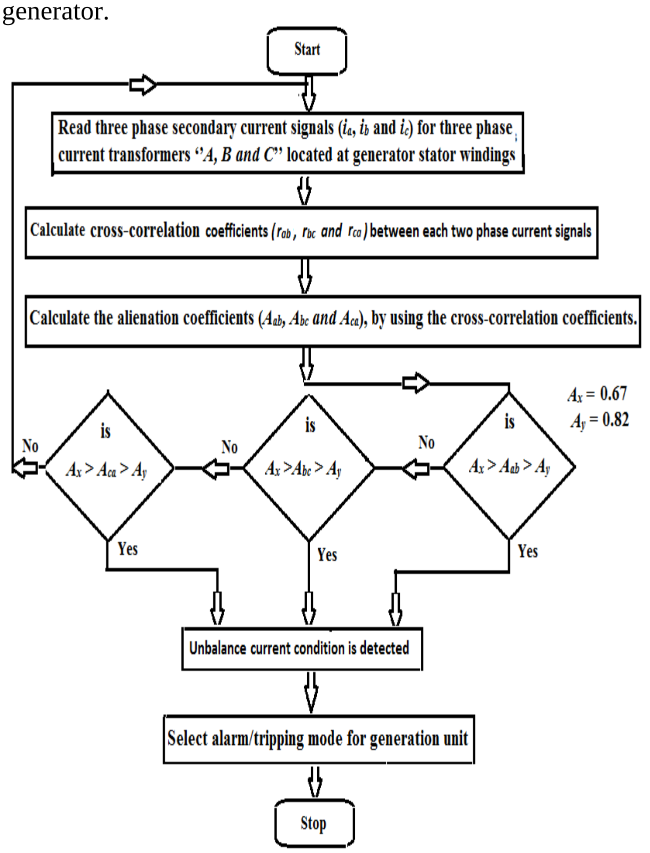

Fig. (1) Flow Chart for Unbalance Current Protection Algorithm Based on Alienation Technique.

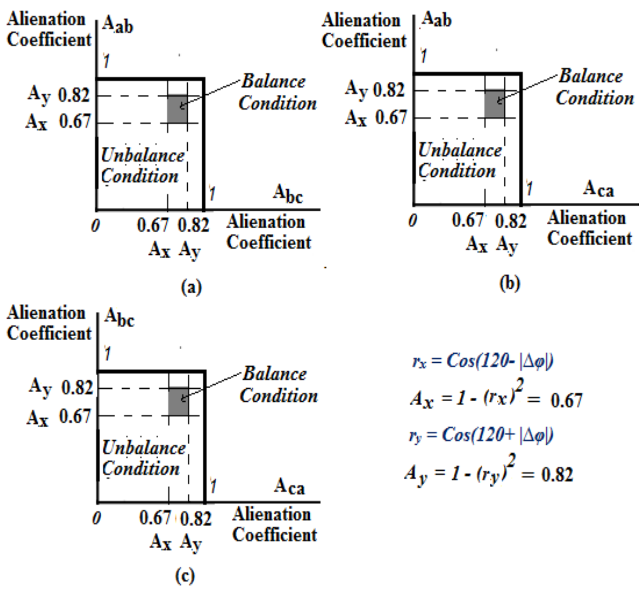

Fig. (2) Unbalance Currents Tripping Characteristics Based on Alienation Coefficient.

III. Power System Description

The single line diagram of power system under study is shown in Fig. (3). The figure shows the input current and voltage signals to the proposed digital relay. Our proposed algorithm does not use the three-phase voltage signals, but they are utilized to view their changes during the various faults. The system parameters are obtained from the Kuriemat power station [19] of the Egyptian 500 KV unified network and are given in Table (2).

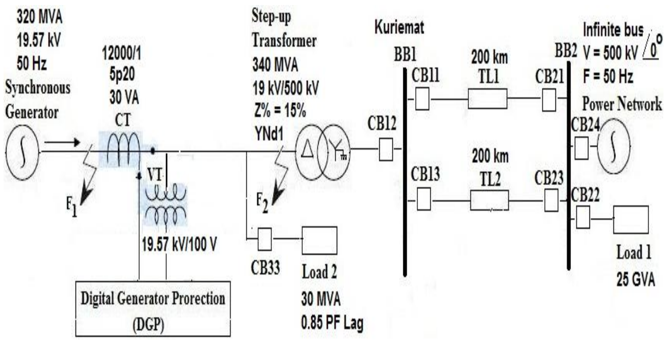

Fig. (3) Single Line Diagram for the Studied Power System.

IV. Simulation Results

An internal fault (F_1) was considered inside the generator protective zone assuming that short circuit is temporary and not resistive. Another fault (F_2) was considered outside the generator protective zone as shown in Fig. (3). To implement the present technique, the studied power system configuration was simulated by using ATP software. The generated and measured three phase current signals, at stator windings terminals, are taken from the protective current transformers of generator zone. The relay's CTs orientation is built for stator winding protection of synchronous generator. The current signals, from ATP software, generated at sampling rate of 100 samples per cycle, this gives a sampling frequency of 5 KHz. The total simulation time is 0.2 Sec (i.e. the total number of samples is 1000). The fault inception time is 0.042 Sec (i.e. at sample 210) from the beginningof simulation time. The developed technique was applied by calculating the alienation coefficient between each two corresponding cycles of each two phase current signals measured at the stator windings terminals, where digital protective relay would normally be installed. The proposed technique, processed by MATLAB software, is able to discriminate between the two different conditions: balance and unbalance currents. Many simulation case studies are done to discriminate between balance and unbalance currents resulting from different types of faults. The unbalance currents are simulated by abnormal conditions such as: single phase-to-ground faults, double phase-to-ground faults, double phase faults, conductor interruption or pole discrepancy for generator circuit breakers. These cases are done under effects of different pre-fault power levels, fault resistances, and fault inception angles in the simulated power system.

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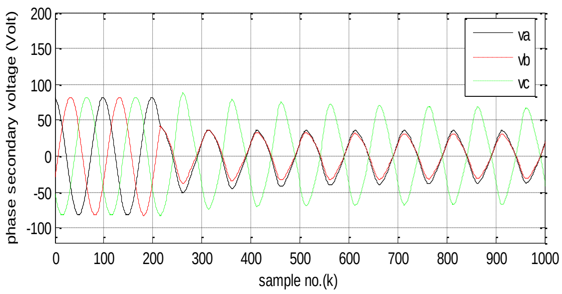
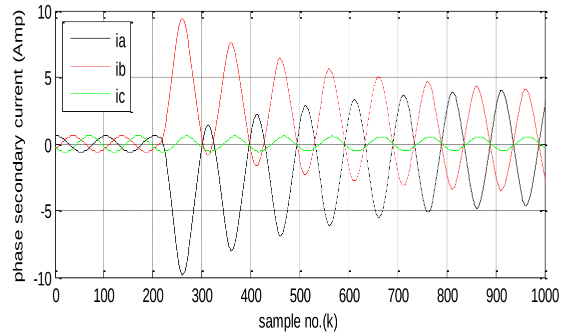
A. External Double Phase Fault (A-B) (Case1)

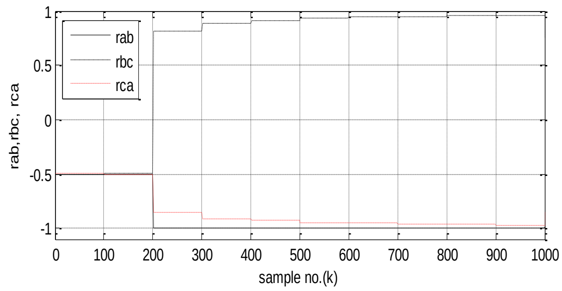
In this case, the unbalance current condition is simulated by external double phase fault to evaluate the performance of the proposed algorithm of unbalance current protection function. The fault is located between the primary side for the step-up transformer and load "2" (aux. load). The fault type is double line (*A*-*B*) fault through a resistance R_f = 0.02 ohm. The fault inception time is 0.042 Sec and the fault clearing time is 0.202 Sec from the beginning of simulation time. The operating conditions of the simulated power system are shown in Table (3). Figs. 4(a-f) show the simulation results in case of external double phases fault through a resistance R_f = 0.02 ohm. The figures show the three-phase secondary voltages and currents at load side, calculated cross-correlation coefficients (r_{ab}, r_{bc} *and* r_{ca}), calculated alienation coefficients (A_{ab}, A_{bc} *and* A_{ca}), trip signal of the proposed digital generator protection, relay operation on the proposed characteristics in case of unbalance currents due to the double phase fault and view of balance currents on the proposed characteristics before fault inception, respectively. Figs. 4(a-b) present the three-phase voltage and current signals at load side of stator windings. The two voltage magnitudes of phases "*A*" and "*B*" during the fault interval are identical and lower than the pre-fault voltage magnitude while the voltage magnitude of phase "*C*" during the fault period is approximately the same pre-fault voltage magnitude. The two phase current magnitudes of phases "*A*" and "*B*" during the fault interval are higher than the pre-fault current magnitudes, with reverse polarity and with high DC component whereas the current magnitude of phase "*C*" during the fault period is approximately the same pre-fault current magnitude. The three cross-correlation coefficients r_{ab}, r_{bc} *and* r_{ca} are shown in Fig. 4(c). The calculated values of cross-correlation coefficients r_{ab}, r_{bc} *and* r_{ca} are equal and close to - 0.5 before fault inception. During fault period, the calculated cross-correlation coefficients r_{ab} and r_{ca} are less than - *0.8* whereas the cross-correlation coefficient r_{bc} is greater than 0.8, as shown in Fig. 4(c). The three alienation coefficients A_{ab}, A_{bc} *and* A_{ca} are shown in Fig. 4(d). The values of alienation coefficients A_{ab}, A_{bc} *and* A_{ca} are equal and close to 0.75 before fault inception. During fault interval, the alienation coefficients A_{ab}, A_{bc}, A_{ca} are less than 0.2, as shown in Fig. 4(d). It is noticed that the alienation coefficient A_{ab} is equal and close to zero; this proves that the fault type is phase-to-phase (*A*-*B*). The values of alienation coefficients (A_{ab}, A_{bc} and A_{ca}) confirm that the system load is balance and unbalance before and during the fault interval, respectively. From the obtained results, it is clear that the proposed technique based on alienation coefficients is good detector to determine the condition of power system currents is balance or unbalance. Their values are inside the range of $1-(Cos(120 \pm |\Delta\varphi|))^2$ in case of normal balance load and becomes outside the range of $1-(Cos(120 \pm |\Delta\varphi|))^2$ in case of unbalance load; $\Delta\varphi$ is the selectable threshold value of unbalanced shift angle and it is chosen as + *5* Degree in the proposed algorithm. When unbalance currents is detected, an alarm signal appears in annunciation module and gives the convenient decision. The external double phase fault condition leads to a trip signal sent for isolation of the generator; this is only executed in the event of no operation for the main protection of synchronous generator or the relay operating time passes a certain definite time. The proposed scheme sets trip signal to high (1), for opening generator CB, as shown in Fig. 4(e). Fig. 4(f) shows relay operation on the proposed characteristics in case of unbalance currents due to double phase fault and Fig. 4(g) shows view of balance currents on the proposed characteristics before fault inception.



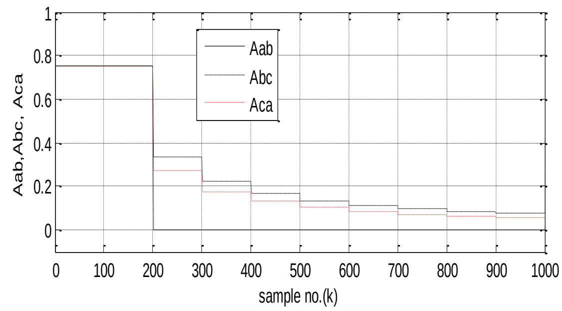
(a) Three phases instantaneous secondary voltages.



(b) Three phases instantaneous secondary currents.



(c) Cross-correlation coefficients r_{ab}, r_{bc} *and* r_{ca}.



(d) Alienation coefficients A_{ab}, A_{bc} *and* A_{ca}.

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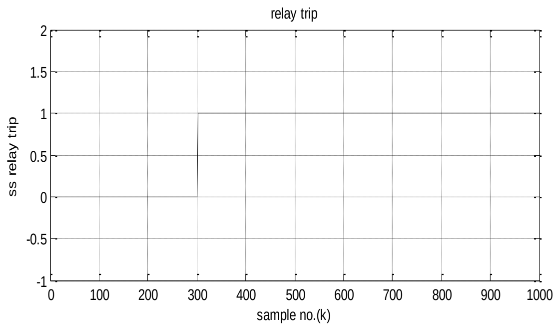
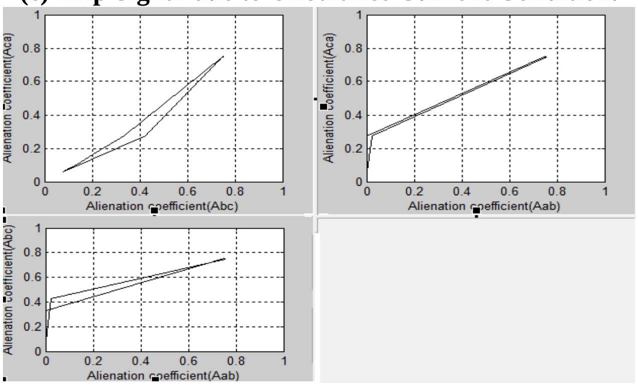
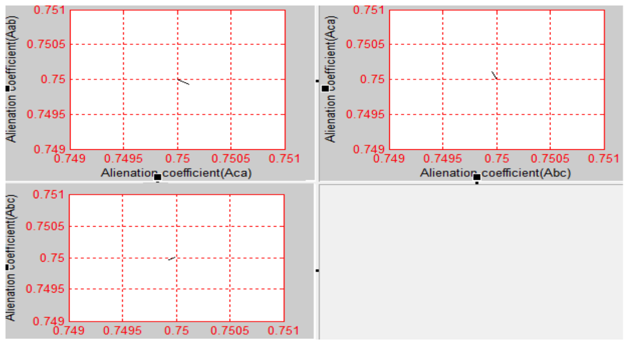


(e) Trip Signal due to Unbalance Current Condition.



(f) Relay Operation on the Proposed Characteristics in Case of Unbalance Currents due to Double Phase Fault.



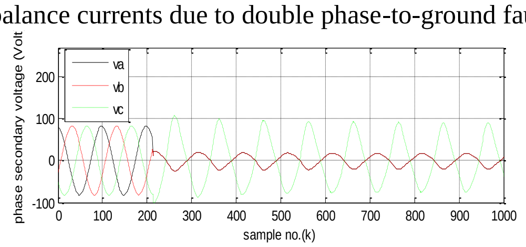
(g) Balance Currents of the Proposed Characteristics Before Fault Inception.

Fig. 4 (a-g) Simulation Results in case of Double Phase Fault (*A-B*).

B. External Double Phase-to-Ground Fault (A-B-G) (Case2)

In this case, the unbalance current condition is simulated by external double phase-to-ground fault to evaluate the performance of the proposed algorithm. Therefore, all parameters are kept as in case 1, except the fault type is changed to external double phase-to-ground fault (*A-B-G*) through a resistance R_f = 1 ohm. The fault inception time is 0.042 Sec and the fault clearing time is 0.202 Sec from the beginning of simulation time. Figs. 5(a-f) show the simulation results in case of external double phase-to-ground fault through a resistance R_f = 1 ohm. The figures show the three-phase secondary voltages and currents at load side, calculated cross-correlation coefficients (r_{ab}, r_{bc} *and* r_{ca}), calculated alienation coefficients (A_{ab}, A_{bc} *and* A_{ca}), trip signal of the proposed digital generator protection, relay operation on the proposed characteristics in case of unbalance currents due to the double phase-to-ground fault. Figs. 5(a-b) present the three-phase voltage and current signals at load side of stator windings. During the fault interval, The two voltage magnitudes of the two faulty phases "*A*" and "*B*" are identical and lower than the pre-fault voltage magnitude while the voltage magnitude of healthy phase "*C*" is greater than pre-fault voltage magnitude. The increase voltage of phase "*C*" (v_c) is occurring because of the fault resistance (1 Ohm) and the resistance (0.77 Ohm) connected between neutral and grounding of the generator. The two phase current magnitudes of the two faulty phases "*A*" and "*B*", during the fault interval, are identical and their values are higher than the pre-fault current magnitudes besides they have contents of high DC component. Whereas the current magnitude of healthy phase "*C*" during the fault period is less than pre-fault current magnitude. The three cross-correlation coefficients r_{ab}, r_{bc} *and* r_{ca} are shown in Fig. 5(c). The calculated values of cross-correlation coefficients r_{ab}, r_{bc} *and* r_{ca} are equal and close to - 0.5 before fault inception. During fault period, the calculated cross-correlation coefficients r_{ab} and r_{ca} are less than *- 0.8* whereas the cross-correlation coefficient r_{bc} is greater than 0.8, as shown in Fig. 5(c). The three alienation coefficients A_{ab}, A_{bc} *and* A_{ca} are shown in Fig. 5(d). The values of alienation coefficients A_{ab}, A_{bc} *and* A_{ca} are equal and close to 0.75 before fault inception. During fault interval, the alienation coefficients A_{ab}, A_{bc}, A_{ca} are less than 0.2, as shown in Fig. 5(d). It is noticed that the values of alienation coefficients (A_{ab}, A_{bc} and A_{ca}) confirm that the system load is balance and unbalance before and during the fault interval, respectively. It is noted that the two secondary current signals of the two faulty phases "*A*" and "*B*", during the fault interval, are distorted (not sine wave) after the sample number 800 because they have high DC component which causes CT saturation occurrence. The saturation condition leads to sudden changes for the values of cross-correlation and alienation coefficients from the beginning of CTs saturation to the remaining of the simulation time as shown in Figs. 5(c-d).

From the obtained results, it is clear that the proposed technique based on alienation coefficients is good indicator to determine the condition of power system currents is balance or unbalance currents of. When unbalance currents is detected, an alarm signal appears in annunciation module and gives the convenient decision. The external double phase-to-ground fault condition leads to a trip signal sent for isolation of the generator; this is only performed in the event of no operation for the main protection of synchronous generator or the relay operating time reaches a certain definite time. The proposed scheme sets trip signal to high (1), for opening generator CB, as shown in Fig. 5(e). Fig. 5(f) shows relay operation on the proposed characteristics in case of unbalance currents due to double phase-to-ground fault.



(a) Three phases instantaneous secondary voltages.

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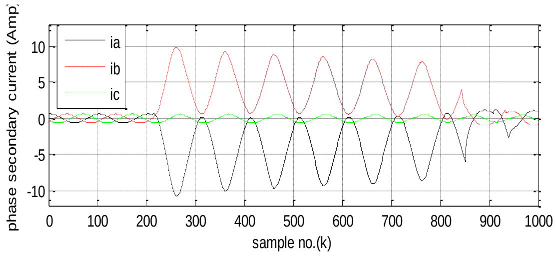
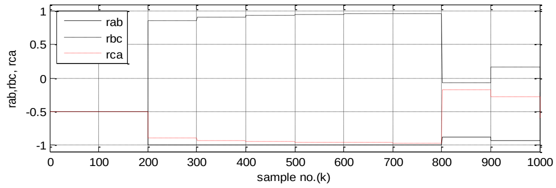
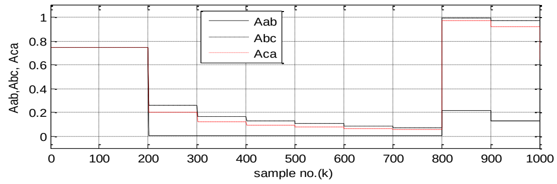


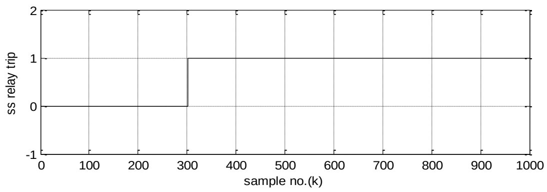
(b) Three phases instantaneous secondary currents.



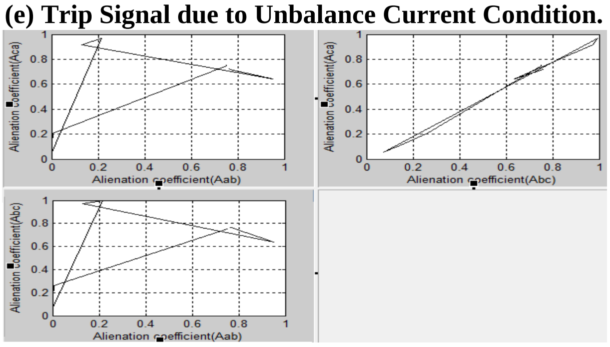
(c) Cross-correlation coefficients r_{ab}, r_{bc} *and* r_{ca}.



(d) Alienation coefficients A_{ab}, A_{bc} *and* A_{ca}.



(e) Trip Signal due to Unbalance Current Condition.

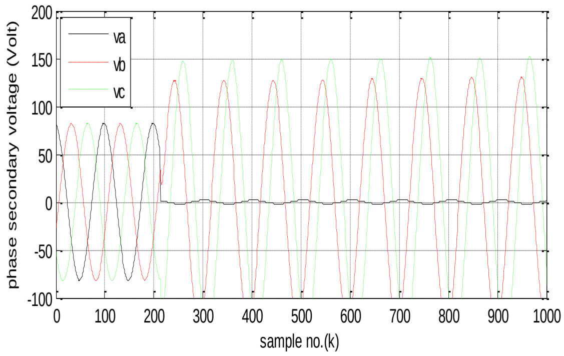


(f) Relay Operation of the Proposed Characteristics in Case of Unbalance Currents due to Double Phase-to-Ground Fault.

Figs. 5 (a-f) Simulation Results in case of Double Phase-to-Ground Fault.

C. External Single Phase-to-Ground Fault (A-G) (Case3)

All parameters are kept as in case "1", except the fault type is changed to external single phase-to-ground fault (*A-G*) through a resistance R_f = 0.02 ohm. In this case, the unbalance current condition is simulated by external single phase-to-ground fault to evaluate the performance of the proposed algorithm. The fault inception time is 0.042 Sec and the fault clearing time is 0.202 Sec from the beginning of simulation time. Figs. 6(a-g) show the simulation results in case of external single phase-to-ground fault (*A-G*) through a resistance R_f = 0.02 ohm. The figures show the three-phase secondary voltages and currents at load side, calculated cross-correlation coefficients (r_{ab}, r_{bc} *and* r_{ca}), calculated alienation coefficients (A_{ab}, A_{bc} *and* A_{ca}), trip signal of the proposed digital generator protection, relay operation on the proposed characteristics in case of unbalance currents due to the single phase-to-ground fault. Figs. 6(a-b) present the three-phase voltage and current signals at load side of stator windings. The two voltage magnitudes of the two healthy phases "*B*" and "*C*" during the fault interval are greater than the pre-fault voltage magnitude (because of the connected resistance, *0.77 ohm*, between the earth and neutral points of stator windings) while the voltage magnitude of phase "*A*" during the fault period is close to zero value and lower than pre-fault voltage magnitude. The two phase current magnitudes of the two healthy phases "*B*" and "*C*" during the fault interval are approximately the same pre-fault current magnitudes whereas the current magnitude of the faulted phase "*A*" during the fault period is higher than pre-fault current magnitude. The three cross-correlation coefficients r_{ab}, r_{bc} *and* r_{ca} are shown in Fig. 6(c). The calculated values of cross-correlation coefficients r_{ab}, r_{bc} *and* r_{ca} are equal and close to - 0.5 before fault inception. During fault period, the calculated cross-correlation coefficients r_{bc} and r_{ca} are greater than - *0.4* whereas the cross-correlation coefficient r_{ab} is less than -0.65, as shown in Fig. 6(c). The three alienation coefficients A_{ab}, A_{bc} *and* A_{ca} are shown in Fig. 6(d). The values of alienation coefficients A_{ab}, A_{bc} *and* A_{ca} are equal and close to 0.75 before fault inception. During fault interval, the alienation coefficients A_{bc}, A_{ca} are greater than 0.85 and the value of alienation coefficient A_{ab} is less than 0.6, as shown in Fig. 6(d). It is noticed that the values of alienation coefficients (A_{ab}, A_{bc} and A_{ca}) prove that the system load is balance and unbalance before and during the fault interval, respectively. From the obtained results, it is clear that the proposed technique based on alienation coefficients is accurate detector to determine balance or unbalance currents of power system. When unbalance currents is detected, an alarm signal appears in annunciation module and gives the convenient decision. The external single phase-to-ground fault condition leads to a trip signal sent for separation of the generator; this is only executed in the event of no operation for the main protection of synchronous generator or the relay operating time reaches a certain definite time. The suggested scheme sets trip signal to high (1), for opening generator CB, as shown in Fig. 6(e). Fig. 6(f) shows relay operation on the proposed characteristics in case of unbalance currents due to single phase-to-ground fault.



(a) Three phases instantaneous secondary voltages.

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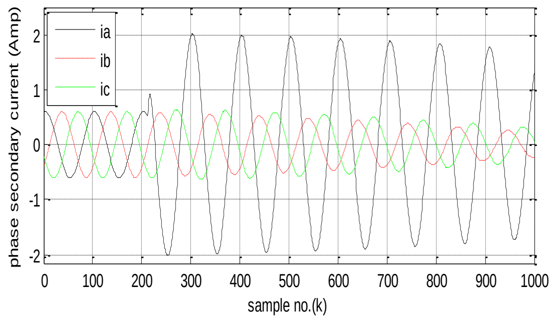
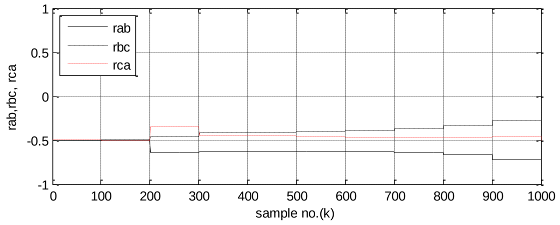
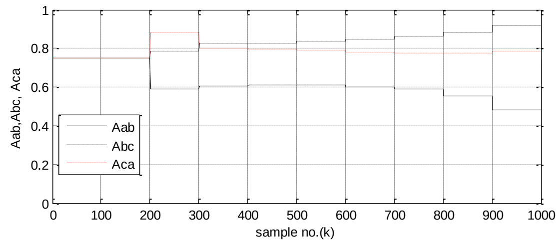


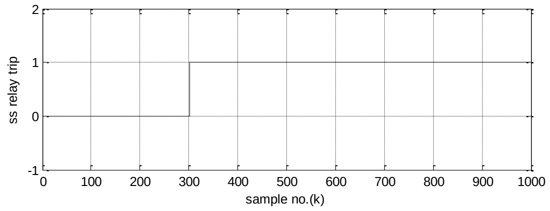
(b) Three phases instantaneous secondary currents.



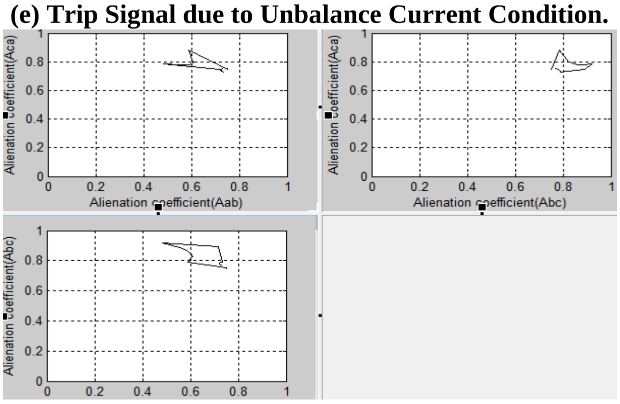
(c) Cross-correlation coefficients r_{ab}, r_{bc} and r_{ca}.



(d) Alienation coefficients A_{ab}, A_{bc} and A_{ca}.



(e) Trip Signal due to Unbalance Current Condition.



(f) Relay Operation of the Proposed Characteristics in Case of Unbalance Currents due to Single phase-to-Ground Fault.

Figs. 6 (a-f) Simulation Results in case of Single Phase-to-Ground Fault (*A-G*).

D. Pole Discrepancy Condition for Generator CB (Case 4)

The present case study aims to evaluate the performance of the proposed algorithm in case of pole discrepancy for generator circuit breakers. In this case, the unbalance current condition is simulated by opening only one phase for the two circuit breakers CB12 (generator CB) and CB33 (aux. load CB) at the same time. CB12 being connected between the secondary side of step-up-transformer and the 500 kV power network is opened for phase "*A*" at instant t_{open} = 0.042 Sec upto 0.202 Sec whereas the other two phases *"B"* and *"C"* are still closed during the total simulation time. Also, the circuit breaker (CB33) connected between the primary side of step-up-transformer and the load 2 (aux. load) is also open for phase "*A*" at t_{open} = 0.042 Sec whereas the other two phases "*B*" and "*C*" are still closed. The operating conditions of the simulated power system are mentioned as in Table (3). Figs. 7(a-g) show the simulation results in case of pole discrepancy for the generator circuit breakers (CB12 and CB33). The figures show the three-phase secondary voltages and currents at load side, calculated cross-correlation coefficients (r_{ab}, r_{bc} *and* r_{ca}), calculated alienation coefficients (A_{ab}, A_{bc} *and* A_{ca}), trip signal from the proposed digital generator protection, relay operation on the proposed characteristics in case of unbalance currents due to the pole discrepancy of the generator circuit breakers. Figs. 7(a-b) present the three-phase voltage and current signals at load side of stator windings. During the pole discrepancy condition, the three phase voltages are unbalanced whereas the pre-pole discrepancy voltages are balanced. The two phase current magnitudes of phases "*A*" and "*B*", during the pole discrepancy period, are lower than pre-pole discrepancy current magnitudes whereas the current magnitude of the phase "*C*", during the same period, is higher than pre-pole discrepancy current magnitude. The three cross-correlation coefficients r_{ab}, r_{bc} *and* r_{ca} are shown in Fig. 7(c). The calculated values of cross-correlation coefficients r_{ab}, r_{bc} *and* r_{ca} are equal and close to - 0.5 before occurrence of pole discrepancy condition. During the period of the pole discrepancy condition, the calculated cross-correlation coefficients r_{bc} and r_{ca} are less than - *0.75* whereas the cross-correlation coefficient r_{ab} is greater than 0.3, as shown in Fig. 7(c). The three alienation coefficients A_{ab}, A_{bc} *and* A_{ca} are shown in Fig. 7(d). The values of alienation coefficients A_{ab}, A_{bc} *and* A_{ca} are equal and close to 0.75 before inception of pole discrepancy condition. During the interval of pole discrepancy condition, the alienation coefficients A_{bc}, A_{ca} are less than 0.4 and the value of alienation coefficient A_{ab} is greater than 0.9, as shown in Fig. 7(d). It is noticed that the values of alienation coefficients (A_{ab}, A_{bc} and A_{ca}) prove that the system load is balance and unbalance before and during the interval of pole discrepancy condition, respectively. From the simulation results, it is obvious that the proposed technique based on alienation coefficients confirms that this case is unbalance currents condition which is resulting from the pole discrepancy events. The unbalance currents causes an alarm signal appears in annunciation module to give the convenient decision. The unbalance currents condition leads to a trip signal; this is performed in the event of the operating time of the protective relay reaches a certain definite time. The suggested scheme sets alarm signal to high (1), as shown in Fig. 7(e). Fig. 7(f) shows the suggested relay operation on the proposed characteristics in case of unbalance currents due to the pole discrepancy condition of generator circuit breakers.

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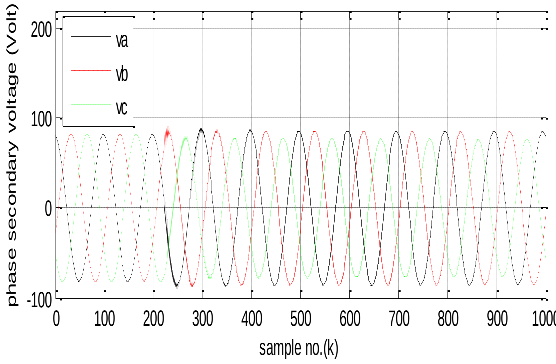
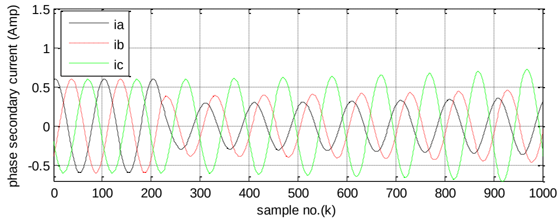
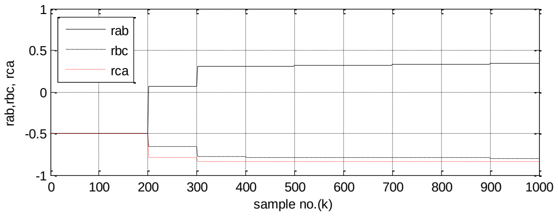


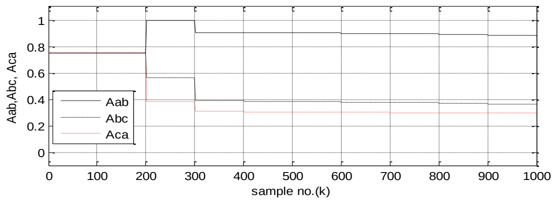
(a) Three phases instantaneous secondary voltages.



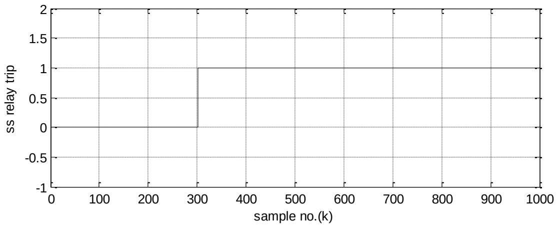
(b) Three phases instantaneous secondary currents.



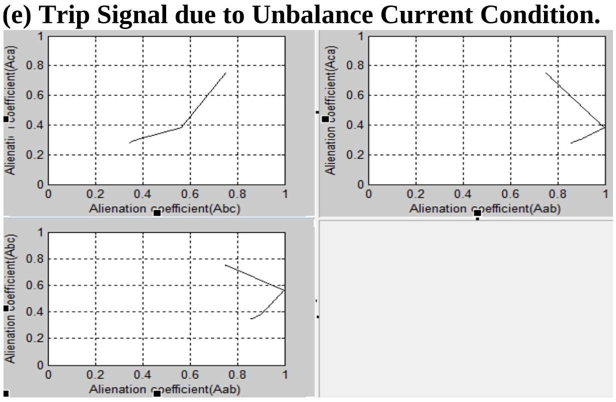
(c) Cross-correlation coefficients r_{ab}, r_{bc} *and* r_{ca}.



(d) Alienation coefficients A_{ab}, A_{bc} *and* A_{ca}.



(e) Trip Signal due to Unbalance Current Condition.



(f) Relay Operation of the Proposed Characteristics in Case of Unbalance Currents due to Pole Discrepancy of Generator Circuit Breakers.

Figs. 7 (a-f) Simulation Results in case of Pole Discrepancy of Generator Circuit Breakers.

V. CONCLUSION

In this paper, a reliable and efficient technique has been presented for protecting generator stator windings against unbalance currents conditions by using alienation coefficients for current signals. ATP software has been used for generating fault data and then processed in MATLAB to get three alienation coefficients calculated between each two phase currents measured at stator windings terminals. These coefficients are used in the proposed algorithm to implement relay logic. Results of case studies of single phase-to-ground, double phases and double phases-to-ground faults under effects of different pre-fault power levels, fault resistances, and fault inception angles are presented in this paper. Pole discrepancy for generator circuit breakers is also studied. Case study results show that the technique used correctly discriminates between balance and unbalance current conditions resulting from the different types of faults located on synchronous generators.

The suggested algorithm has the following features:

1. Introduced a new protection technique for synchronous generator against unbalance current conditions based on alienation algorithm.
2. Three-phase current measurements are sufficient to implement this technique and the power system element data is not used.
3. The new technique has the advantages of new closed characteristic based on three alienation coefficients of each two phase currents thus determining and decreasing the balance zone.
4. Succeeded in identifying all unbalance currents of different fault types and producing a trip signal for generator CBs within a selectable certain time after unbalance currents detection.
5. The suggested alienation technique is characterized by being simple, reliable and can be implemented practically, thus it can be used as a base for implementing a cheap and reliable digital protective relay against unbalance currents conditions for synchronous generators.
6. It is accurate to identify unbalance current conditions in different types of short-circuit faults and pole discrepancy of circuit breaker.
7. Fast method, as the time taken by this method is about 20 ms (for a 50-Hz system).
8. Control of algorithm operation speed by selecting correlated window in correlation and alienation calculations, this mean adjustable speed (i.e. half-cycle, one cycle).
9. Control of proposed algorithm sensitivity (adjusting of pick up value for alienation coefficients) by selecting alienation setting and correlated window.
10. It is quite effective over a wide range of a pre-fault power levels, fault resistances and fault inception angles.
11. The effects of DC components and harmonics are eliminated with estimation of alienation coefficients.

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APPENDIX

Table (1) Alienation coefficient ranges at different balance/unbalance current conditions for synchronous generator and relay action.

Generator Condition	***Alienation Coefficients*** A_x = 0.67 and A_y = 0.82 A_{x1} = 0.59 and A_{y1} = 0.88	***Relay Action***
1. Normal balance current condition	$A_x < A_{ab} < A_y$, $A_x < A_{bc} < A_y$ and $A_x < A_{ca} < A_y$	*Blocking*
2. Unbalance current condition	$(A_{x1} \leq A_{ab} \leq A_x$ or $A_y \leq A_{ab} \leq A_{y1})$, $(A_{x1} \leq A_{bc} \leq A_x$ or $A_y \leq A_{bc} \leq A_{y1})$ or $(A_{x1} \leq A_{ca} \leq A_x$ or $A_y \leq A_{ca} \leq A_{y1})$	*Cooling system operation*
3. Severe unbalance current condition	$A_{x1} > A_{ab} > A_{y1}$, $A_{x1} > A_{bc} > A_{y1}$ or $A_{x1} > A_{ca} > A_{y1}$	*Tripping*

Table (2) Power system parameters data.

Power system parameter	***Data***
Synchronous Generator **(Sending source):** *Rated Volt-ampere / Rated line voltage / Rated frequency* *Number of poles /Neutral grounding impedance (R_n)*	*320 MVA / 19.57 kV / 50 Hz* *2/ 0.77 ohm*
Step-up Transformer: *Rated Volt-ampere* *Transformation voltage ratio* *Connection primary/secondary* *Primary winding impedance (Z_p)* *Secondary winding impedance (Z_s)* *Vector group* *Z%*	*340 MVA* *19 kV /500 kV* *Delta/Star earthed neutral* *0.0027 + j0.184 ohm* *0.7708 + j 61.8 ohm.* *YNd1* *15%*
Transmission Lines: *+ve sequence R* *Zero sequence R* *+ve sequence XL* *Zero sequence XL* *+ve sequence 1/Xc* *Zero sequence 1/Xc* *Transmission line long (Km)*	*0.0217ohm /km* *0.247 ohm/km* *0.302 ohm/km* *0.91 ohm/km* *3.96 micro-mho /km* *2.94 micro-mho /km* *200 Km*
Main Load (load 1): *Load 1 Volt-ampere*	*25 GVA at PF = 0.85 lag*
Aux. Load (load 2): *Load 2 Volt-ampere*	*30 MVA at PF = 0.85 lag*
Power Network **(Receiving source):** *Nominal line voltage* *Voltage phasor angle phase* *Nominal frequency* *Volt-ampere short circuit*	*500kV (1pu)* *0^0* *50 Hz* *25 GVA ($i_{s.c}$ = 10 kA)*
Current Transformer (CT): *CTR* *Rated burden* *Class*	*12000/1* *30 VA* *5p20*
Voltage Transformer (VT): *VTR*	*19570/100 V*

Table (3) Operating conditions of electrical components.

Electrical component **(operating** ***condition)***	***Data***
$F_{operated}$	*50 Hz*
Load 2 (aux. load)	*10.85 + j 6.72 Ohm*
Generator operating power angle (δ_1)	*10 Degree*
Operating phase peak voltage of generator	*16063 Volt*
Generator grounding impedance	*0.77 ohm*

REFERENCES

1. "Protective Relays Applications Guide," The English Electric Company Limited, Relay Division, Stafford, 1975.
2. C. J. Mozina, "IEEE Tutorial on the Protection of Synchronous Generators", IEEE Tutorial Course, IEEE Power Engineering Society Special Publ., no. 95 TP102, 1995.
3. M. S. Sachdev and D. W. Wind, "Generator differential protection using a hybrid computer," IEEE Trans. Power Apparatus System, PAS-92 (1973) 2063-2072.
4. N.W. Kinhekar, Sangeeta Daingade and Ajayshree Kinhekar, “Current Differential Protection of Alternator Stator Winding,” Paper submitted to the International Conference on Power Systems Transients (IPST2009) in Kyoto, Japan June 3-6, 2009.
5. Grainger J, Stevenson Jr WD. Power systems analysis electrical engineering. McGraw-Hill International Editions; 1994.
6. ABB Automation Products, 'Negative sequence overcurrent relay and protection assemblies' 1999. Available: http://www.abb.mu/product/us/9AAC710454.aspx Accesed on: 15 Feb 2012.
7. P. K. Dash, O. P. Malik, and G. S. Hope, "Digital differential protection of a generating unit scheme and real-time test results," IEEE Transactions oxn Power Apparatus and Systems, vol. PAS-96, no. 2, March/April 1977.
8. P. K. Dash, O. P. Malik, and G. S. Hope, "Fast generator protection against internal asymmetrical faults," IEEE Transactions on Power Apparatus and Systems, vol. PAS-96, no. 5, September/October 1977.
9. Q. Usta, M. Bayrak, M.A. Redfern, "A New Digital Relay for Generator Protection against Asymmetrical Faults", IEEE Transaction on Power Delivery, Yol. 17, No.1, January 2002, pp. 54-59.
10. T. Bach, et al., "Determining negative sequence currents of turbine generator rotors," in Electrical Machines and Systems, 2009. ICEMS 2009. International Conference on, 2009, pp. 1-6.

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11. F. Elneweihi, et al., "Negative-sequence overcurrent element application and coordination in distribution protection," Power Delivery, IEEE Transactions on, vol. 8, pp. 915-924, 1993.
12. Muhammad Mohsin Aman, Muhammad Qadeer Ahmed Khan and Mohd Noor Abdullah, "Modeling and Simulation of Digital Negative Sequence Relay for Unbalanced Protection of Generator" 2012 IEEE international power engineering and optimization conference (PEOCO2012), Melaka, Malaysia: 6-7 June 2012.
13. ATP - version 3.5 for Windows 9x/NT/2000/XP - Users' Manual Preliminary Release No. 1.1 - October 2002.
14. W. Hauschild, and W. Mosch, "Statistical Techniques for High Voltage Engineering", hand book, English edition published by peter pere grinus Ltd., London, United Kingdom, chapter 2, pp. 78-79, 1992.
15. Edwards, A. L. "The Correlation Coefficient." Ch. 4 in an Introduction to Linear Regression and Correlation. San Francisco, CA: W. H. Freeman, pp. 33-46, 1976.
16. Snedecor, G. W. and Cochran, W. G. "The Sample Correlation Coefficient r and Properties of r." 10.1-10.2 in Statistical Methods, 7th ed. Ames, IA: Iowa State Press, pp. 175-178, 1980.
17. Press, W. H.; Flannery, B. P.; Teukolsky, S. A.; and Vetterling, W. T. "Linear Correlation", Cambridge, England: Cambridge University Press, pp. 630-633, 1992.
18. Spiegel, M. R. "Correlation Theory." Ch. 14 in Theory and Problems of Probability and Statistics, 2nd ed. New York: McGraw-Hill, pp. 294-323, 1992.
19. Instruction Manual for Generator Electrical Equipment, Upper Egypt Electricity Production Company, Elkureimat Π 750 MW Combined Cycle Project, Steam Turbine Generator & Auxiliaries (Generator Electrical Equipment), Hitachi, Ltd., Tokyo Jaban,2006.

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