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A new scheme based on correlation technique for generator stator fault detection-part I

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Abstract: In modern digital protection systems, a correlation technique is recently used for study and analysis. In this paper, a correlation technique is developed for fault detection, classification and direction discrimination. The proposed technique is able accurately to identify the different types of faults that may occur in synchronous generator stator winding. Three line-current measurements are required for both generator sides. The suggested technique performs the fault classification task within half-cycle. Thus, the algorithm is well suited for implementation in a digital generator protection scheme. The used technique is applied for El-kuriemat power station unit that produces 320 MVA. Alternative transient program (ATP) and MATLAB programs are used to implement the proposed technique in this paper.

Keywords: Power System, Generator Protection, Fault Classification, Correlation Coefficient, Internal Faults, ATP-EMTP

1. 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. Generator protection has dual protection objectives. Generator faults may occur due to stator earth and phase faults, inter-turn faults, unbalanced stator currents, overheating, overvoltage, undervoltage, loss-of-excitation, over excitation, over speed, generator motoring, rotor earth faults and other abnormal conditions, such as out-of-step.

The conventional protection schemes for protecting large synchronous generators have many drawbacks, faults that might take place near the neutral point of stator windings are not detected in case of high neutral grounding impedance for generator, besides inter-turn faults are not usually discovered. In addition, the advent of large power stations and highly interconnected power systems makes rapid fault isolation to maintain system stability.

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 to detect stator faults of generators.

Electric power utilities and industrial plants traditionally use electromechanical and solid-state relays for protecting synchronous generators [3]. With the advent of digital technology, researchers and designers have made significant progress in developing protection systems based on digital and microprocessor techniques [4-5]. Several microprocessor based algorithms for detecting stator winding faults have been proposed. Sachdev and Wind [6] developed an algorithm that uses instantaneous differences between line and neutral end currents for detecting phase faults. Tao and Morrison [7] have used the discrete Fourier Transform and Walsh functions to calculate the phasors of the fundamental frequency and third harmonic voltages. 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 [8-9] in which the discrimination against external faults is achieved by monitoring the direction of the negative sequence power flow at the machine terminals. This paper proposing a fault detection, classification and direction discrimination scheme based on correlation technique. The technique measures the currents at the both ends of stator windings and uses the calculated auto/cross-correlation coefficients for the two-side currents of each phase, for making relay trip or no trip decision. The suggested technique can operate accurately, during half-cycle period of the fundamental frequency.

2. ATP/EMTP Modeling of Synchronous Generator

ATP library has many built-in models including rotating machines, transformers, surge arrestors, switches, transmission lines and cables [10]. The model SM59 provides detailed dynamic modeling of synchronous machine. In addition to rated voltage, current and frequency, the model needs d and q axis steady state, transient and sub-transient reactance, value of moment of inertia, damping coefficient and number of poles. When dynamics of the machine is not required, sinusoidal voltage source model Type-14 can be used. Thus the package model Type-14 is preferred for modeling synchronous generator to analyze the internal faults located on stator windings; this is valid during the subtransient time.

The synchronous machine model in ATP-EMTP is used to do fault analysis to study the suggested protection scheme based on correlation concept for fault detection. The proposed protection algorithm is implemented by using MATLAB package and is examined under different distances on stator windings and various types of internal, external faults that may occur in the simulated power system.

3. Proposed Technique

In this paper, ATP-EMTP software is used to get reliable simulation results during faults. The suggested protection scheme is based on correlation concept in order to detect the faults on stator windings. Currents at both ends of each phase of the generator stator windings are measured and stored in a file where it is used for correlation estimation. On both sides of generator stator windings, the currents entering stator windings are first side as i_{1a}, i_{1b} and i_{1c} as shown in Fig. 1. The second side currents are i_{2a}, i_{2b}, and i_{2c}.

Generated data measured by current meters at the both ends of stator windings is stored in a file; this data is in the discrete sampled form. These current samples of both sides are processed in MATLAB to estimate auto/cross-correlation coefficients for two-side currents of each phase. This means nine correlation coefficients are obtained for three phases, six auto-correlation coefficients and three cross-correlation coefficients.

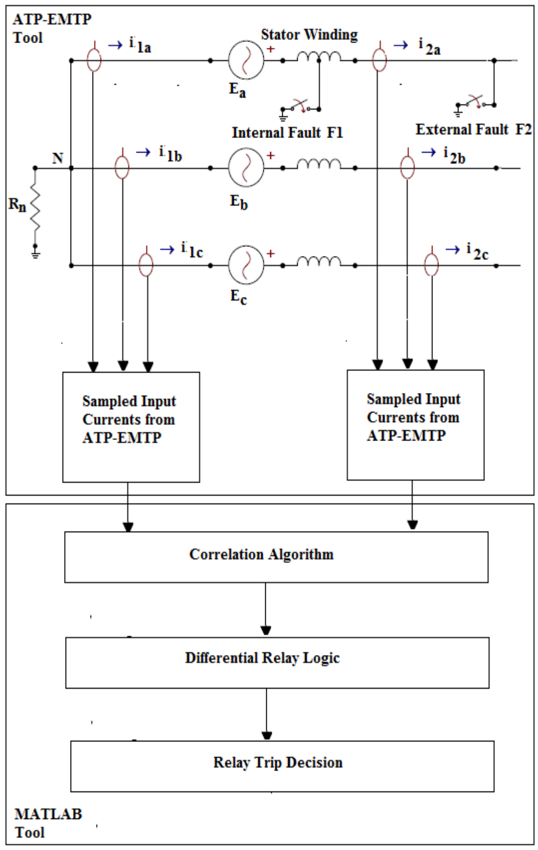


Figure 1. *Block diagram of proposed scheme.*

3.1. Basic Principles

This technique is based on auto/cross-correlation coefficients estimation [11-12] for each phase current signals ((i_{1s}, i_{2s}). The linear correlation coefficient, in general r_s, measures the strength and the direction of a linear relationship between two variables. It is sometimes referred to as the Pearson product moment correlation coefficient in honor of its developer Karl Pearson, it is a dimensionless quantity; that is, it does not depend on the units employed. The value of correlation is such that $-1 \leq r_s \leq +1$.

The proposed differential protection algorithm based on correlation technique has the following procedures:

1- Read discrete sampled current of two sides (i_{1s} and i_{2s}) for each phase ''s'' of stator windings (obtained from ATP tool).

2- Make digital smoothing for sampled currents i_{1s} and i_{2s} for each phase ''s'' at neutral and load sides, respectively. The smoothed sampled currents are shown in Eqs. (1-6).

$$I_{1s}(k-1) = (5i_{1s}(k-1) + 2i_{1s}(k) - i_{1s}(k+1)) / 6 \quad (1)$$

$$I_{1s}(k) = (i_{1s}(k-1) + i_{1s}(k) + i_{1s}(k+1)) / 3 \quad (2)$$

$$I_{1s}(k+1) = (-i_{1s}(k-1) + 2i_{1s}(k) + 5i_{1s}(k+1)) / 6 \quad (3)$$

Where,

$I_{1s}(k-1)$, $I_{1s}(k)$ *and* $I_{1s}(k+1)$: the smoothed values of sampled currents for phase ''s'' at neutral side corresponding to sampling instants *k -1, k* and *k + 1,* respectively.

$i_{1s}(k-1)$, $i_{1s}(k)$ and $i_{1s}(k+1)$: the measured sampled currents for phase ''s'' at neutral side corresponding to sampling instants *k -1, k* and *k + 1,* respectively (Data obtained from physical measurement often contains errors).

$$I_{2s}(k-1) = (5i_{2s}(k-1) + 2i_{2s}(k) - i_{2s}(k+1))/6 \quad (4)$$

$$I_{2s}(k) = (i_{2s}(k-1) + i_{2s}(k) + i_{2s}(k+1))/3 \quad (5)$$

$$I_{2s}(k+1) = (-i_{2s}(k-1) + 2i_{2s}(k) + 5i_{2s}(k+1))/6 \quad (6)$$

Where,

$I_{2s}(k-1)$, $I_{2s}(k)$ and $I_{2s}(k+1)$: the smoothed values of sampled currents for phase ''s'' at load side corresponding to sampling instants *k -1, k* and *k + 1,* respectively.

$i_{2s}(k-1)$, $i_{2s}(k)$ and $i_{2s}(k+1)$: the measured sampled currents for phase ''s'' at load side corresponding to sampling instants *k -1, k* and *k + 1,* respectively.

3- Calculate auto-correlation coefficient (r_{i1s})

Auto-correlation coefficient (r_{i1s}) is calculated between two successive windows (each window has *m* samples) shifted from each other by one cycle interval for the instantaneous values of neutral current (i_{1s}) of phase ''s''. Eq. (7) shows the calculation of auto-correlation (r_{i1s}).

$$r_{i1s} = \frac{\sum_{k=1}^{m} i_{1s}(k) i_{1s}(k+N) - \frac{1}{m}\sum_{k=1}^{m} i_{1s}(k) \sum_{k=1}^{m} i_{1s}(k+N)}{\left(\sqrt{\sum_{k=1}^{m}(i_{1s}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{1s}(k))^2}\right) \times \left(\sqrt{\sum_{k=1}^{m}(i_{1s}(k+N))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{1s}(k+N))^2}\right)} \quad (7)$$

Where,

r_{i1s}: auto-correlation coefficient between two successive windows (each window has *m* samples) shifted from each other by one cycle interval for the instantaneous values of current (i_{1s}) at first side, of phase ''s''.

N: the number of samples per cycle used in the simulation.

4- Calculate auto-correlation coefficient (r_{i2s})

The auto-correlation coefficient (r_{i2s}) is calculated between two successive windows (each window has *m* samples) shifted from each other by one cycle interval for the instantaneous values of load current (i_{2s}) of phase ''s''. Eq. (8) shows the calculation of auto-correlation (r_{i2s}).

$$r_{i2s} = \frac{\sum_{k=1}^{m} i_{2s}(k) i_{2s}(k+N) - \frac{1}{m}\sum_{k=1}^{m} i_{2s}(k) \sum_{k=1}^{m} i_{2s}(k+N)}{\left(\sqrt{\sum_{k=1}^{m}(i_{2s}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{2s}(k))^2}\right) \times \left(\sqrt{\sum_{k=1}^{m}(i_{2s}(k+N))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{2s}(k+N))^2}\right)} \quad (8)$$

Where,

r_{i2s}: auto-correlation coefficient between two successive windows (each window has *m* samples) shifted from each other by one cycle interval for the instantaneous values of current (i_{2s}) at (load) second side of phase ''s''.

5- Calculate cross-correlation coefficient (r_{i12s})

Cross-correlation coefficient (r_{i12s}) is estimated between *m* samples for a phase ''s'' current (i_{1s}) signal at first side near neutral point and the corresponding *m* samples for the same phase ''s'' current (i_{2s}) signal at second side near generator terminal. The selected *m* samples are four-samples which are used as a correlated small window in the differential protection function to obtain fast acting fault protection. The cross-correlation coefficient (r_{i12s}) is calculated as shown in Eq. (9).

$$r_{i12s} = \frac{\sum_{k=1}^{m} i_{1s}(k) i_{2s}(k) - \frac{1}{m}\sum_{k=1}^{m} i_{1s} \sum_{k=1}^{m} i_{2s}}{\left(\sqrt{\sum_{k=1}^{m}(i_{1s}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{1s}(k))^2}\right) \times \left(\sqrt{\sum_{k=1}^{m}(i_{2s}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{2s}(k))^2}\right)} \quad (9)$$

Where,

r_{i12s}: cross-correlation coefficient for *m* sampled currents between the two sides, neutral and load, of phase ''s'' for protected generator.

s: the phase designation *A, B or C.*

m: the number of samples per window to be correlated used in the algorithm (four-samples are selected in the algorithm).

$i_{1s}(k)$: the sampled current values at instant *k* for neutral (first) side of phase ''s''.

$i_{2s}(k)$: the sampled current values at instant *k* for load (second) side of phase ''s''.

6- Tripping action of the algorithm relies on the following conditions:

(a) If r_{i1s} and $r_{i2s} = 1$(for all phases) & $r_{i12s} = 1$ (for all phases), then this case is normal operation condition.

(b) If r_{i1s} *or* $r_{i2s} < 1$ (for any phase) & $r_{i12s} = 1$(for all phases), then this case is external fault condition.

(c) If r_{i1s} *or* $r_{i2s} < 1$(for any phase) & $r_{i12s} < 1$ (for any phase) at the same window and for the same phase, then this case is internal fault condition.

Tripping characteristic for the proposed differential protection is shown in Fig. 2. The characteristic illustrates two areas, blocking area in case of external fault condition and tripping area in case of internal fault condition. To confirm internal fault occurrence, the cross-correlation coefficient values are less than one with preset value (0.9 is selected as threshold value).

The process of fault detection, faulted phase(s) identification and fault zone determination either internal or external start altogether in parallel with a maximum execution time of 10 msec. The cross-correlation coefficient (r_{i12s}) determines the faulted phase (s) and decides whether the fault is external or internal in case of $r_{i12s} < 1$, whereas the auto-correlation coefficient (r_{i1s} or r_{i2s}) determines the fault condition in general, in case of $r_{i1s} < 1$or $r_{i2s} < 1$. But the later two coefficients do not decide the fault being external or internal and do not identify the faulted phase(s). The auto-correlation coefficient, r_{i1s} *or* r_{i2s} is used for fault occurrence confirmation, discrimination between healthy and external fault conditions and CT saturation detection besides the cross-coefficient r_{i12s}.

7- Finally a tripping mode is selected for generation unit;

four methods are used for isolating a generator once a fault has been detected [13-14]. They fall into four groups as follows: simultaneous tripping, generator tripping, unit separation and sequential tripping

3.2. CT Saturation Detection

The phenomenon of transient CT saturation during external faults causes false differential current in conventional differential relay; consequently a suggested algorithm is introduced for CT saturation detection as follows:

(a) If the auto/cross-correlation coefficients (r_{i1s}) and (r_{i12s}) for phase ''s'' are suddenly decreased in the same window (simultaneously), an internal fault is detected.

(b) If the auto-correlation coefficient (r_{i1s}) is firstly dropping whereas the cross-correlation coefficient (r_{i12s}) decreases later (shifting time of T_{sat} for phase ''s''), the fault is then an external fault with CT saturation. The interval (T_{sat}) is defined as the time-to-saturation from the beginning of fault detection, where it is supposed to have a minimum time of 2.5 msec (1/8 cycle) in case of severe CT saturation.

Auto/cross-correlation coefficient ranges (limits) at different fault conditions for synchronous generator are included in Table 1.

Table 1. *Auto/cross-correlation coefficient ranges at different fault conditions.*

Generator condition	r_{i12s} Cross-correlation	r_{i1s} or r_{i2s} Auto-correlation	Relay action
1. Normal operation	1 for all 3-phase	1 for all 3-phase	Blocking
2. External fault	1 for all 3-phase	< 1 at least one phase	Blocking
3. Internal fault	< 1 at least one phase	< 1 at least one phase	Tripping
4. External fault with CT saturation (assume only one side CT saturated)	1 (during the interval from fault inception to CT saturation starting) at least one phase	< 1 at least one phase	Blocking

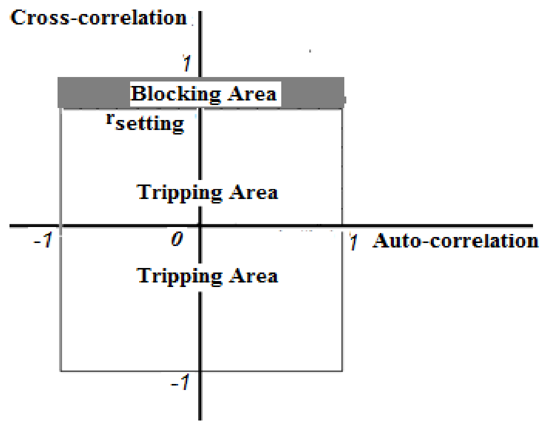


Figure 2. *Tripping Characteristic for the Proposed Differential Protection.*

4. Power System Description

The single line diagram of power system under study is shown in Fig. 3. The three phase wiring of the synchronous generator (Type-14) used in simulation is shown in Fig. 4. The synchronous generator model makes reference to the work described in article [15-17]. Their proposed simulation of internal fault includes the addition of two voltage sources of reverse polarities to each other in the faulted phase. Also each of the generator reactance in the EMTP reactance data card are reduced by a value of ''x'' which is equal to the sub-transient reactance of the sound portion of the windings.

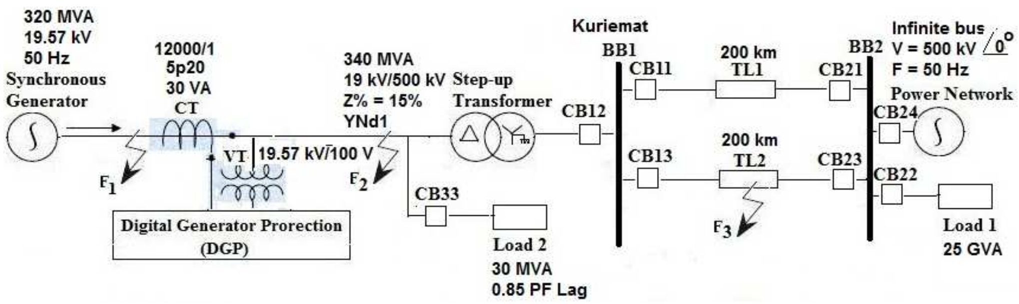


Figure 3. *Single Line Diagram for the Studied Power System.*

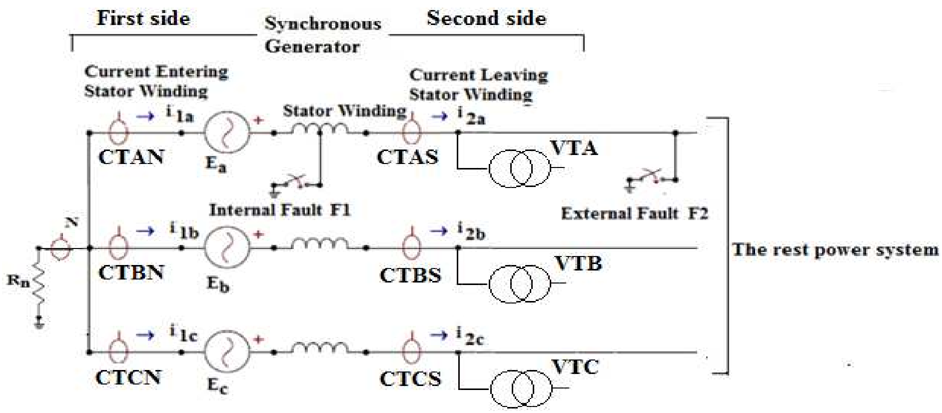


Figure 4. *Synchronous Machine Model*

The system parameters are obtained from the Kuriemat power station [18] of the Egyptian 500 KV unified network and are given in Appendix 1.

5. Simulation Results

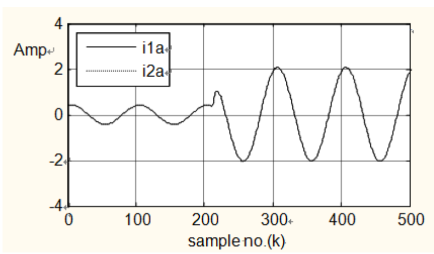
An internal single-line to ground fault (F_1) was located on stator winding of the generator. Another single-line to ground fault (F_2) was considered outside the generator protection zone as shown in Fig.4. The relay's CTs orientation is built for proper functioning of the proposed stator winding protection. The current signals, from ATP-EMTP software, generated at sampling rate of 100 samples per cycle, this gives a sampling frequency of 5 KHz. The total simulation time is 0.1 Sec (i.e. the total number of samples is 500). The fault inception time is 0.042 Sec (at sample 210) from the beginning of simulation time.

5.1. Case 1: External Fault without CT Saturation Condition

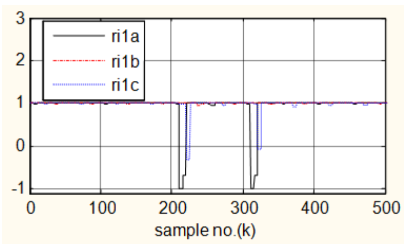
An external single-line to ground fault (F_2) is located out of the generator protection zone at the primary side of step-up-transformer. The fault type is single phase *A*-to-ground assuming that short circuit is not resistive. The operating conditions of the simulated power system are shown in Appendix 2.

Figures 5 (a-g) show the simulation results in case of external single line-to-ground fault. The Figures present the three phase secondary current signals at the two receiving and sending end sides, and their auto/cross-correlation coefficients. In this case, it is noticed that the phase *A* secondary currents for neutral and load sides during the fault are identical and higher than the pre-fault currents; their values are nearly 4.8 times the pre-fault currents as shown in Fig. 5(a). Phase *B* secondary currents for the two sides during the fault are identical and higher than the pre-fault currents; their values are approximately 1.1 times the pre-fault currents as shown in Fig. 5(b), however; phase *C* secondary currents for the two sides during the fault are identical and lower than the pre-fault current, their values are approximately 0.92 times the pre-fault currents as shown in Fig. 5(c). The calculated cross-correlation coefficients (r_{i12a}, r_{i12b}, r_{i12c}) are equal and close to unity before and during fault occurrence as presented in Fig. 5(d). The algorithm calculates cross-correlation coefficient between each two corresponding windows for secondary current signals at the two receiving and sending end sides. The calculated auto-correlation coefficients (r_{i1a}, r_{i1b}, r_{i1c}, r_{i2a}, r_{i2b}, r_{i2c}) are equal and close to unity before fault occurrence, and they decrease with fault occurrence (see Figures 5(e-f)).

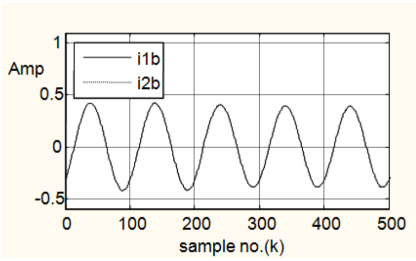
A trip flag depends on the cross-correlation values, if their values are less than unity then a trip signal is sent for isolation generator CB. But this case is external fault condition and no tripping signal is issued as shown in Fig. 5(g). To assure that this case is external fault and not normal operation, auto-correlation coefficients is estimated between each two windows of load or neutral current signal shifted from each other by one cycle. The auto-correlation values are closely to unity for neutral and load current signals in case of normal operation and their values are less than one in case of external faults.



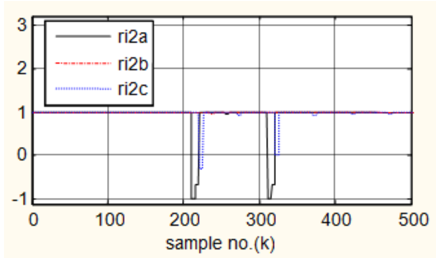
(a) The current signals i_{1a}, i_{2a} for case 1.



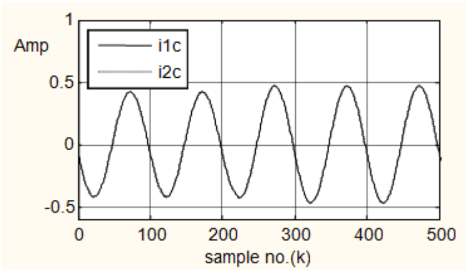
(f) Auto-correlation coefficients r_{i1a}, r_{i1b} and r_{i1c}.



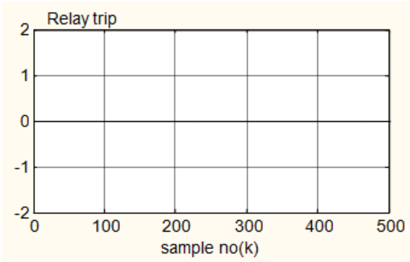
(b) The current signals i_{1b}, i_{2b} for case 1.



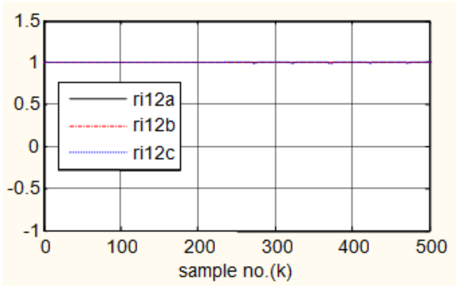
(g) Auto-correlation coefficients r_{i2a}, r_{i2b} and r_{i2c}.



(c) The current signals i_{1c}, i_{2c} for case 1.



(h) No trip flag in case of external fault.



(d) Cross-correlation coefficients r_{i12a}, r_{i12b} and r_{i12c}.

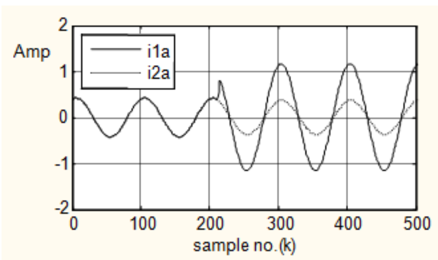
Figures 5 (a-g). *Three phase current signals and their auto/cross-correlation coefficients for case 1.*

5.2. Case 2: Internal Fault Condition

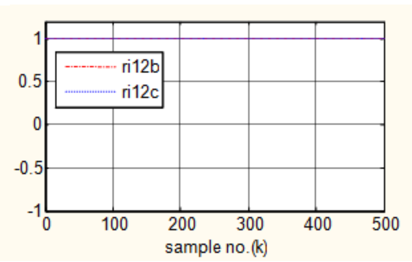
In this case, all parameters are kept as in case 1 except the external fault type (F_2) is changed to become internal fault type (F_1). At operating power angle of generator δ_I is 0 degree, a single-line to ground fault (F_1) is located on phase A for stator winding. Earth faults are simulated at different locations on stator winding such as 2%, 5%, 7%, 10%, 15%, 20%, 30%, 40%, 50% distance points from the generator neutral. Figures 6(a-h) show the simulation results for case 2 in case of internal fault at 40% of stator winding. The Figures present the three phase secondary current signals at the two receiving and sending end sides and their auto/cross-correlation coefficients ($r_{i1a}, r_{i1b}, r_{i1c}, r_{i2a}, r_{i2b}, r_{i2c}$) and ($r_{i12a}, r_{i12b}, r_{i12c}$).

Appendix 3 shows the change in the Auto/cross-correlation coefficients for current signals of each phase in cases SLG (a-g) fault at different locations on stator winding (internal faults) at $\delta_I = 0$ and $R_f = 0$ ohm.

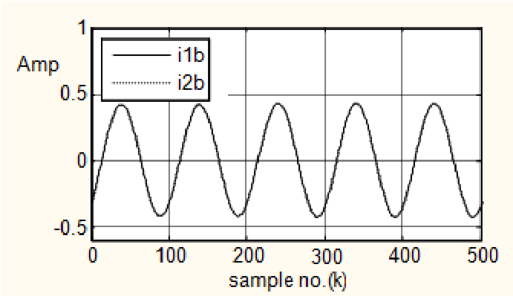
From the obtained results, it clearly appears that the proposed technique for differential algorithm succeeded in differentiating between internal and external faults occurring on the generator stator besides identifying fault type and faulted phase(s). The technique has also the advantage of detecting ground faults occurring near the neutral point thus decreasing the dead zone to 2%.



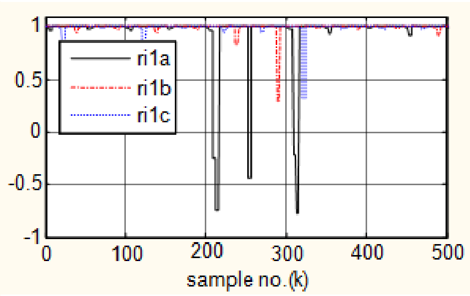
(a) The current signals i_{1a}, i_{2a} for case 2.



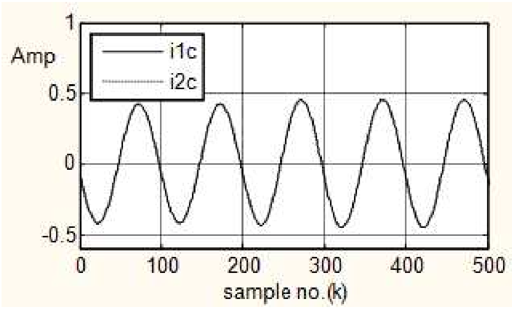
(e) Cross-correlation coefficients r_{i12b} and r_{i12c}.



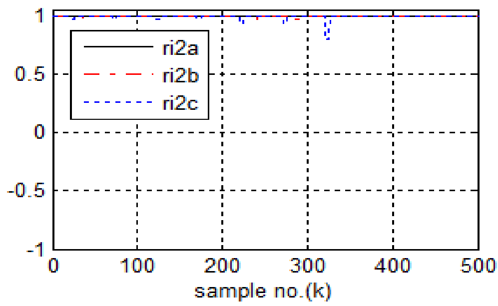
(b) The current signals i_{1b}, i_{2b} for case 2.



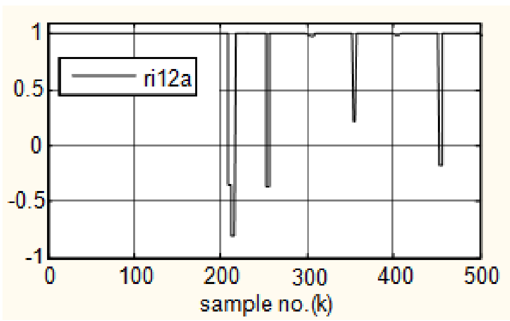
(f) Auto-correlation coefficients r_{i1a}, r_{i1b} and r_{i1c}.



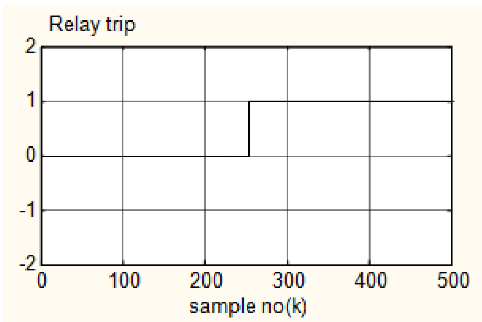
(c) The current signals i_{1c}, i_{2c} for case 2.



(g) Auto-correlation coefficients r_{i2a}, r_{i2b} and r_{i2c}.



(d) Cross-correlation coefficient r_{i12a}.



(h) Relay trip flag for case 2.

Figures 6 (a-h). *Three phase current signals and their auto/cross-correlation coefficients for case 2.*

6. Conclusions

In this paper, a reliable and efficient technique has been presented for detecting generator stator winding internal and external faults by using correlation algorithm.

ATP-EMTP software has been used for generating fault data and then processed in MATLAB to get auto/cross-correlation coefficients of two-side currents for each phase of stator windings. These coefficients are used in the proposed algorithm to implement relay logic. Results of case studies of single line to ground faults at different locations on stator winding and various fault types are presented. Case study results show that the technique used correctly discriminates between internal and external faults on the stator winding.

The suggested algorithm has the following features:

1. Introduced a new detection technique for internal faults on stator windings, the new technique has the advantages of avoiding CT saturation effect, detecting ground faults occurring near the neutral point thus decreasing the dead zone to 2% only, and avoid the effects of switching, DC components and harmonics
2. Succeeded in identifying fault type, location and faulted phase(s), and produced a trip signal within 10 msec after fault occurrence.
3. Has the advantage of using the algorithm of differential protection for CT saturation detection; whereas most conventional differential protection algorithms require a separate algorithm for detecting CT saturation.
4. The suggested auto/cross-correlation technique is characterized by being simple, fast, reliable and accurate and can be implemented practically, thus it can be used as a base for implementing a cheap and reliable digital protective relay for synchronous generators.

Appendix

Appendix 1. *Power system parameters data.*

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

Appendix 2. *Operating conditions of electrical components.*

Electrical component (operating condition)	Data
$F_{operated}$	50 Hz
Load 1 (main load)	8.5 + j 5.26 Ohm
Load 2 (aux. load)	10.85 + j 6.72 Ohm
Generator operating power angle *(δ_1)*	0 Degree
Operating phase peak voltage of generator	16063 Volt
Generator grounding impedance	0.77 ohm

Appendix 3. *Auto/cross-correlation coefficients of each phase in cases of internal SLG (a-g) faults, δ_1 = 0, R_f = 0 ohm.*

	Fault Type SLG (a-g) Fault % Fault location on stator winding								
	50%	**40%**	**30%**	**20%**	**15%**	**10%**	**7%**	**5%**	**2%**
	Cross-corr. Between the two currents of neutral and load sides								
r_{i12a} pre-fault	1	1	1	1	1	1	1	1	1
r_{i12a} during-fault	- 0.93	- 0 .89	- 0.83	- 0.73	- 0.63	- 0.46	-0.26	+ 0.03	+ 0.85
r_{i12b} pre-fault	1	1	1	1	1	1	1	1	1
r_{i12b} during-fault	1	1	1	1	1	1	1	1	1
r_{i12c} pre-fault	1	1	1	1	1	1	1	1	1
r_{i12c} during-fault	1	1	1	1	1	1	1	1	1
	Auto-corr. of current at neutral side								
r_{i1a} pre-fault	1	1	1	1	1	1	1	1	1
r_{i1a} during-fault	- 0.90	- 0.87	- 0.81	- 0.71	- 0.62	- 0.46	- 0.26	+ 0.03	+ 0.84

	Fault Type SLG (a-g) Fault % Fault location on stator winding								
	50%	**40%**	**30%**	**20%**	**15%**	**10%**	**7%**	**5%**	**2%**
	Cross-corr. Between the two currents of neutral and load sides								
r_{i1b} pre-fault	1	1	1	1	1	1	1	1	1
r_{i1b} during-fault	0.94	0.95	0.96	0.97	0.97	0.97	0.98	0.98	0.98
r_{i1c} pre-fault	1	1	1	1	1	1	1	1	1
r_{i1c} during-fault	0.92	0.94	0.95	0.96	0.96	0.96	0.96	0.96	1
	Auto-corr. of current at load side								
r_{i2a} pre-fault	1	1	1	1	1	1	1	1	1
r_{i2a} during-fault	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
r_{i2b} pre-fault	1	1	1	1	1	1	1	1	1
r_{i2b} during-fault	0.94	0.95	0.96	0.97	0.97	0.97	0.98	0.98	0.98
r_{i2c} pre-fault	1	1	1	1	1	1	1	1	1
r_{i2c} during-fault	0.92	0.94	0.95	0.96	0.96	0.96	0.96	0.96	0.96

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