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Experimental Results and Technique Evaluation Based on Alienation Coefficients for Busbar Protection Scheme-Part II

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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 busbar protection against all ten types of shunt faults, which may locate in busbar protection zone, under different loading levels, fault resistances and fault inception angle. It does not need any extra equipment as it depends only on the three-line currents measurements, of all feeders connected to the protected busbar, which are mostly available at the relay location. It is able to perform fault detection, fault confirmation, faulty phase selection and determine the fault location in about a half-cycle period. Thus, the alienation technique is well suited for implementation in digital protection schemes. The technique is efficient to detect current transformer saturation conditions without needing any additional algorithm. The effects of DC components and harmonics are eliminated with estimation of alienation coefficients. The proposed scheme is applied for an experimental circuit. LABVIEW program and MATLAB package are used to implement the proposed technique.***

Index Terms— ***Busbar protection, current transformer saturation, fault detection, internal and external faults, alienation coefficient, LABVIEW software, MATLAB.***

I. INTRODUCTION

A busbar is a critical element of a power system, as it is the point of convergence of many circuits, transmission, generation, or loads. The effect of a single bus fault is equivalent to many simultaneous faults and usually, due to the concentration of supply circuits, involves high current magnitudes. High-speed busbar protection is often required to limit the damaging effects on equipment and system stability or to maintain service to as much load as possible. Differential protection is the most sensitive and reliable method for protecting a station buses. The phasor summation of all the measured current entering and leaving the bus must be zero unless there is a fault within the protective zone. For a fault not in the protective zone, the faulted circuit is energized at a much higher level, near CT saturation or with varying degrees of CT saturation, giving rise to possible high false differential currents. Under ideal conditions, the secondary current developed by CT will be the primary current divided by the CT turns ratio. However, the CT secondary current will not be a sine wave when the flux in the CT core reaches into the saturated region. The factors affecting this are secondary burden, primary current magnitude, asymmetry in the primary current, remanent flux in the CT core, saturation voltage, fault inception angle and CT turns ratio [1]. Actually, the DC component has far more influence in producing severe saturation than the AC fault current.

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Direct current saturation is particularly significant in bus differential relaying systems, where highly differing currents flow to an external fault through the current transformers of the various circuits. Dissimilar saturation in any differential scheme will produce operating current. The problem of CT saturation is not popular in case of an internal fault conditions. Severe current transformer saturation will occur if the primary circuit DC time constant is sufficiently long and the DC component sufficiently high. The DC component arises because the current in an inductance cannot change instantaneously and the steady- state current, before and after a change, must lag (or lead) the voltage by the proper power-factor angle. Many methods are used to avoid the CT saturation. The problem of CT saturation is eliminated by air-core CT's called "linear couplers''. In fact, these CT's have a disadvantage that very little current can be drawn from the secondary, because so much of the primary magneto-motive force is consumed in magnetizing the core. Another method is used to increase the size of the CT core to obtain a higher saturation voltage than a calculated value [2]. Another one uses special core material to withstand large flux density [3]. These options present mechanical and economic difficulties. Recently, many software techniques are provided to solve these problems and each method has its advantage and disadvantage. Some techniques uses a DC component equal and opposite to that in the primary circuit generated by a circuit added to the secondary winding [4]. Other techniques used a magnetization curve and the equivalent circuit of a CT for compensating secondary current of CT during saturation condition; these techniques has practical difficulties, as it depends on CT parameters /characteristics and secondary burdens [5]. Also, Artificial Neural Networks (ANNs) are used in this area to learn the nonlinear characteristics of CT magnetization and restructures the waveform based on the learned characteristics. This method could not be applied to different CT's due to the variations of CT's saturation characteristics and the secondary burdens [6]. Some other algorithms prevent relay operation during CT saturation [7]. This may result in longer trip times. A method for compensating the secondary current of CT's is based on the ideal proportional transient secondary fault current. A portion of measured secondary current following the fault occurrence is described using regression analysis [8]. Another method utilizes four consequent samples, during the unsaturated portion of each cycle, for solving a set of equations to obtain the constants of the primary fault current equation for re-constructing the secondary current during the saturated part.

The scheme calculates the correct primary time constant by repeating the calculations of the algorithm using different values of time constant and chooses the value that gives the smallest error [9]. A digital technique for protecting busbars presented in [10] uses positive- and negative-sequence models of the power system in a fault-detection algorithm. While phase voltages and currents are used to detect faults, parameters of the power system are not used. Another method called current phase comparison is presented in [11], which can achieve reliable busbar protection with minimum CT performance requirements. Thousands of RTDS test and MATLAB analyses have been performed, which proved that the stability of busbar protection can be greatly improved by this algorithm. The presented principle in paper [12] describes a methodology for protecting busbars. The method uses the ratio between the fault component voltage and the fault component differential current of the busbar to detect faults, which is defined as the fault component integrated impedance. The fault component integrated impedance of an external fault reflects the capacitance impedance of the busbar whereas that of an internal fault reflects the parallel connection result of the impedances of all the feeders connected to the busbar. As a result, the magnitudes of the integrated impedances are quite different between an external fault and an internal fault. A model parameter identification based bus-bar protection principle is proposed in paper [13]. An inductance model can be developed when an internal fault occurs on bus. By taking the inductance and the resistance of the model as the unknown parameters to be identified, the equivalent instantaneous impedance and the dispersion of the parameter can be calculated. Utilizing their difference, the external fault and the internal fault with different current transformer (CT) saturation extent can be distinguished. Through-out this work a new technique for busbar protection based on alienation coefficients is suggested. The technique measures the three-line currents of each circuit connected to the protected busbar, which are mostly available at the relay location. The alienation coefficient is calculated between input and output currents of each phase for busbar in order to make relay trip or no trip decision. The suggested technique takes into consideration the wide variations of operating conditions such as loading levels, fault resistance and fault inception angle.

II. PROPOSED TECHNIQUE

A. Basic Principles

In this paper, LABVIEW software [14] is used to get reliable experimental results before, during and after different fault conditions which are located in and out the protective zone of busbar. Three-phase current signals of each circuit, connected to the busbar, are obtained and converted to discrete sampled form by data acquisition card. These current samples of each phase are processed online in MATLAB script (inserted in LABVIEW package) to get an alienation coefficient [15-16]. The coefficient is estimated between the input and output phase current signals of the busbar. The suggested technique is based on alienation concept in order to determine busbar fault type whether internal or external to make relay trip or no trip decision, respectively. The calculations of the alienation coefficients are processed for each two corresponding half-cycles of the two currents to get high-speed operation for busbar protection.

B. Alienation Coefficients Calculation

The variance between any two signals is defined as the alienation coefficient [17-19], which is obtained from correlation coefficient; thus alienation coefficient is a good proposed technique for making busbar protection against different fault conditions located on the busbar element. Alienation coefficient calculated between the two phase currents entering and leaving the bus can recognize a variance between them and to operate in response to it. This coefficient is derived from cross-correlation coefficient. Cross-correlation coefficient (r_a) is calculated between each two corresponding windows of the two sampled currents (i_{a1} and i_{a2}) entering and leaving the phase *"A"* bus, where the two windows are shifted from each other with a time interval $h\Delta t$. The coefficient (r_a) between the two signals (i_{a1} and i_{a2}) 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_b *and* r_c) are given by Equations (2) and (3), respectively.

$$r_a = \frac{\sum_{k=1}^{m} i_{a1}(k) i_{a2}(k+h\Delta t) - \frac{1}{m}\sum_{k=1}^{m} i_{a1}(k) \sum_{k=1}^{m} i_{a2}(k+h\Delta t)}{\left(\sqrt{\sum_{k=1}^{m}(i_{a1}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{a1}(k))^2}\right) \times \left(\sqrt{\sum_{k=1}^{m}(i_{a2}(k+h\Delta t))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{a2}(k+h\Delta t))^2}\right)} \quad (1)$$

$$r_b = \frac{\sum_{k=1}^{m} i_{b1}(k) i_{b2}(k+h\Delta t) - \frac{1}{m}\sum_{k=1}^{m} i_{b1}(k) \sum_{k=1}^{m} i_{b2}(k+h\Delta t)}{\left(\sqrt{\sum_{k=1}^{m}(i_{b1}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{b1}(k))^2}\right) \times \left(\sqrt{\sum_{k=1}^{m}(i_{b2}(k+h\Delta t))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{b2}(k+h\Delta t))^2}\right)} \quad (2)$$

$$r_c = \frac{\sum_{k=1}^{m} i_{c1}(k) i_{c2}(k+h\Delta t) - \frac{1}{m}\sum_{k=1}^{m} i_{c1}(k) \sum_{k=1}^{m} i_{c2}(k+h\Delta t)}{\left(\sqrt{\sum_{k=1}^{m}(i_{c1}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{c1}(k))^2}\right) \times \left(\sqrt{\sum_{k=1}^{m}(i_{c2}(k+h\Delta t))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{c2}(k+h\Delta t))^2}\right)} \quad (3)$$

Where,

r_a: The cross-correlation coefficient calculated between input and output current signals (i_{a1} and i_{a2}) for the phase *"A"* of busbar.

r_b: The cross-correlation coefficient calculated between input and output current signals (i_{b1} and i_{b2}) for the phase *"B"* of busbar.

r_c: The cross-correlation coefficient calculated between input and output current signals (i_{c1} and i_{c2}) for the phase *"C"* of busbar.

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

$i_{a1}(k)$: the summation input current values at instant k for phase ''*A*'' of busbar.

$i_{a2}(k)$: the summation output current values at instant k for phase ''*A*'' of busbar.

$i_{b1}(k)$: the summation input current values at instant k for phase ''*B*'' of busbar.

$i_{b2}(k)$: the summation output current values at instant k for phase ''*B*'' of busbar.

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i_{c1} *(k):* the summation input current values at instant *k* for phase ''*C*'' of busbar.

i_{c2} *(k):* the summation output current values at instant *k* for phase ''*C*'' of busbar.

The alienation coefficient (A_a), calculated between the two current signals (i_{a1} and i_{a2}), is obtained from cross-correlation coefficient (r_a) and it is given in Equation (4). Also alienation coefficients (A_b *and* A_c) are given by Equations (5) and (6), respectively.

$$A_a = 1 - (r_a)^2 \quad (4)$$

$$A_b = 1 - (r_b)^2 \quad (5)$$

$$A_c = 1 - (r_c)^2 \quad (6)$$

Where,

A_a: The alienation coefficient calculated between the two current signals (i_{a1} and i_{a2}) for the phase *"A"* of busbar.

A_b: The alienation coefficient calculated between the two current signals (i_{b1} and i_{b2}) for the phase *"B"* of busbar.

A_c: The alienation coefficient calculated between the two current signals (i_{c1} and i_{c2}) for the phase *"C"* of busbar.

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 a value of alienation coefficient to be between "0" and "1".

C. Busbar Protection Procedures

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

1- Read discrete sampled of three-phase secondary current signals for three-phase current transformers of each circuit connected to the protected busbar (obtained from data acquisition card tool).

2- Calculate input and output current values (i_{a1} *(k)*, i_{a2} *(k)*, i_{b1} *(k)*, i_{b2} *(k)*, i_{c1} *(k)* and i_{c2} *(k)*) for each phase of the protected busbar.

3- Calculate cross-correlation coefficient calculated between the input and output current signals for each phase of busbar as given by Equations (7), (8)

$$r_b = \frac{\sum_{k=1}^{m} i_{b1}(k) i_{b2}(k) - \frac{1}{m}\sum_{k=1}^{m} i_{b1}(k)\sum_{k=1}^{m} i_{b2}(k)}{(\sqrt{\sum_{k=1}^{m}(i_{b1}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{b1}(k))^2}) \times (\sqrt{\sum_{k=1}^{m}(i_{b2}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{b2}(k))^2})} \quad (8)$$

and (9),

$$r_a = \frac{\sum_{k=1}^{m} i_{a1}(k) i_{a2}(k) - \frac{1}{m}\sum_{k=1}^{m} i_{a1}(k)\sum_{k=1}^{m} i_{a2}(k)}{(\sqrt{\sum_{k=1}^{m}(i_{a1}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{a1}(k))^2}) \times (\sqrt{\sum_{k=1}^{m}(i_{a2}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{a2}(k))^2})} \quad (7)$$

$$r_c = \frac{\sum_{k=1}^{m} i_{c1}(k) i_{c2}(k) - \frac{1}{m}\sum_{k=1}^{m} i_{c1}(k)\sum_{k=1}^{m} i_{c2}(k)}{(\sqrt{\sum_{k=1}^{m}(i_{c1}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{c1}(k))^2}) \times (\sqrt{\sum_{k=1}^{m}(i_{c2}(k))^2 - \frac{1}{m}(\sum_{k=1}^{m} i_{c2}(k))^2})} \quad (9)$$

4- Calculate the alienation coefficients (A_a*,* A_b *and* A_c), by using the calculated cross-correlation coefficients (r_a*,* r_b *and* r_c), respectively as given in Equations (4), (5) and (6).

In case of no internal fault condition, it is known that the total sum of input currents is equal to the total sum of output currents for each phase of busbar. Alienation coefficient, calculated between the input and output currents for each phase, must be zero unless there is a fault within the bubar protective zone. Thus it is developed for faults detection, fault confirmation, and faulty phase selection in our proposed scheme. The proposed technique is able to accurately identify the condition of phase(s) involved in all ten types of shunt faults that may occur in busbars under different loading levels, fault resistances and fault inception angles. Our proposed algorithm calculates the three-phase alienation coefficients (A_a*,* A_b *and* A_c); Normally, the value of cross-correlation coefficient is "1" because the phase shift is 0^0 in case of ideal normal operation or external fault without CT saturation ($r_a = r_b = r_c = Cos\ (0^o) = 1$), hence ($A_a = A_b = A_c = 1- (Cos\ (0^o))^2 = 0.0$). In cases of internal faults located on the protected bubar, the previous rule is not verified. No ideal operation condition in power system. To avoid this drawback, operation under healthy condition is restricted by alienation coefficients limits (A_x), where, $A_x = 0.05$.

5- Fault detection and faulty phase selection

To implement our technique, three tasks are starting in parallel: fault detection, fault confirmation, and faulty phase selection as follows:

■ Fault detection (initiation)

A transition is detected for each phase of busbar if: $\Delta I > 20\%\ I_n$, where I_n is the bubar nominal current.

■ Faulty phase selection

- Fault confirmation and faulty phase selection are done according to the following sequences:

Three-phase current alienation coefficients values (A_a*,* A_b *and* A_c) are calculated. If fault is detected, phase current alienation values are sorted and compared. The possible fault cases are:

(a) If the three-phase alienation coefficients values are equal or less than A_x, where the selected A_x is 0.05, then the condition is external fault or normal operation.

- If $A_a \le A_x$, $A_b \le A_x$ and $A_c \le A_x$, the fault type is external or normal operation.

(b) If the three-phase alienation coefficients values are greater than A_x, then the fault is three-phase and internal.

- If $A_a > A_x$, $A_b > A_x$ and $A_c > A_x$, the fault is three-phase and internal (a-b-c fault).

(c) If the two-phase alienation coefficients values are nearly zero (or equal or less than A_x), while the third phase alienation coefficient is greater than A_x, the fault is internal single phase-to-ground.

- If $A_a > A_x$, $A_b \le A_x$, $A_c \le A_x$, the fault is single phase- to-ground and internal (a-g fault).
- If $A_b > A_x$, $A_a \le A_x$, $A_c \le A_x$, the fault is single phase- to-ground and internal (b-g fault).
- If $A_c > A_x$, $A_a \le A_x$, $A_b \le A_x$, the fault is single phase- to-ground and internal (c-g fault).

(d) If the two-phase alienation coefficients values are greater than A_x, while the third phase alienation coefficient is equal or less than A_x, the fault is internal and it may be phase-to-phase or double phase-to-ground and internal.

- If $A_a > A_x$, $A_b > A_x$, $A_c \le A_x$, the fault is internal and it may be phase-to-phase (a-b fault) or double phase-to-ground (a-b-g fault).
- If $A_a \le A_x$, $A_b > A_x$, $A_c > A_x$, the fault is internal and it may be phase-to-phase (b-c fault) or double phase-to-ground (b-c-g fault).

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- If $A_a > A_x$, $A_b \le A_x$, $A_c > A_x$, the fault is internal and it may be phase-to-phase (a-c fault) or double phase-to-ground (a-c-g fault).

(e) To make sure of distinguishing between double phase and double phase-to-ground faults, the alienation coefficient is calculated between the two faulted phases currents for the input (or output) phase currents of the protected busbar). If the value of alienation is nearly zero, the fault is phase-to-phase.

- If $A_{ab} \le A_x$ the fault is phase-to-phase and internal (a-b fault) otherwise the fault is double phase-to-ground and internal (a-b-g fault).
- If $A_{bc} \le A_x$ the fault is phase-to-phase and internal (b-c fault) otherwise the fault is double phase-to-ground and internal (b-c-g fault).
- If $A_{ac} \le A_x$ the fault is phase-to-phase and internal (a-c fault) otherwise the fault is double phase-to-ground and internal (a-c-g fault).

6- Tripping/blocking action of the algorithm relies on the following rules for the following conditions:

(a) Normal operation condition,

- If $A_a \le A_x$, $A_b \le A_x$ *and* $A_c \le A_x$ (for each phase of busbar), then this case is (healthy) normal operation or external fault without CT saturation condition (where, $A_x = 0.05$ is selected) and the scheme holds trip signal to low (0).

- $A_a \approx A_b \approx A_c \le A_x$

(b) Internal fault condition

- If $A_a > A_x$, $A_b > A_x$ or $A_c > A_x$ (for any phase of the protected busbar), then this case indicates to internal fault condition inside the protective busbar zone. Hence the faulted busbar must be isolated from the remaining power system, and the scheme sets trip signal to high (1).

- $T_{bb} = 0$ *Sec, where,* T_{bb} = Operating time (in Sec) for busbar protection function.

(c) External fault with CT saturation condition

- If $A_a \le A_x$, $A_b \le A_x$ *and* $A_c \le A_x$ during the first quarter-cycle after fault detection because of the free saturated portion of secondary current signals, then this case is external fault with CT saturation condition. In this condition, the alienation coefficient is greater than A_x during the distorted portions of current signal and it is less than A_x during unsaturated portions. This event makes the scheme holds trip signal to low (0). The fault type's conditions, alienation coefficient limits and relay action are given in Table (1).

In this paper, the experimental part is presented including the following items:

- ➢ Building up the laboratory circuit for busbar differential protection based on alienation technique.
- ➢ Obtain test results in various cases of fault conditions.
- ➢ Verify the performance of the proposed differential protection based on alienation technique.

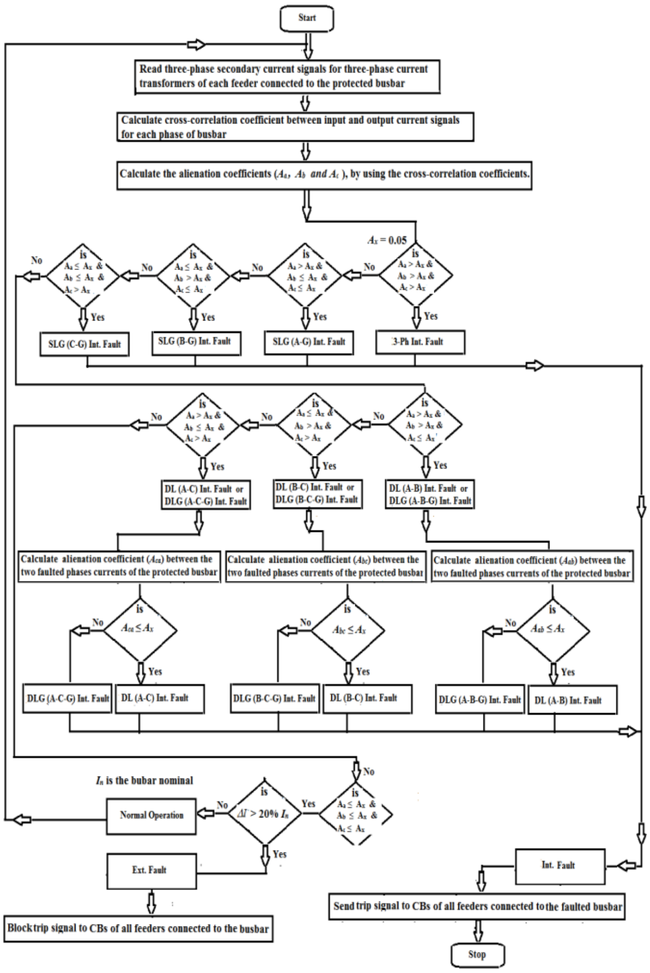

Fig. 1 Flow Chart for Busbar Protection Algorithm Based on Alienation Technique

III. LABORATORY CIRCUIT DESCRIPTION

The laboratory circuit consists of the following main parts (as shown in Figure 2):

(a) Power supply (as source)

The power supply has the following data:

Nominal voltage = 220 V
Frequency = 60 Hz

(b) Single phase induction motor (as inductive load)

The single phase induction motor has the following data:

Rated active power = 150 Watt
Rated apparent power = 860 VA
Nominal voltage = 230 Volt
Rated current = 3.8 Amp
Frequency = 60 Hz

(c) Two Current Transformers (CTs)

CT turns ratio = 50/5 Amp
R_b = 0.15 Ohm for each CT

(d) Leads (wires)

(e) Harmonic power clamp meter

(f) On/off switch for power supply

(g) Data acquisition card (NI USB-6008/6009 Device)

The data acquisition card (DAC) is used to convert the analog data into a suitable digital data that can be used via a digital processor. The National Instruments USB-6008/6009 is data acquisition (DAQ) device.

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The NI USB-6008/6009 device provides connection to eight analog input (AI) channels, two analog output (AO) channels, 12 digital input/output (DIO) channels, and a 32-bit counter with a Full-Speed USB interface. The Data acquisition card is characterized by 14-bit input resolution, 8 input channels single ended or 4 input channels differential and the sampling rate is 48 kHz. The DAC is adjusted to operate in differential mode. Two input channels for two side's currents per phase are used with a sampling frequency of 1 kHz for each channel.

(h) Digital relay (computer)

PC computer is used to virtually simulate the intelligent electronic device relay. The computer in this case is functioning as digital relay. The specification of this computer is HP Pavilion Entertainment PC, processor: 2.1 GHZ and installed memory (RAM): 3.00 GB.

IV. EXPERIMENTAL RESULTS

Testing of the proposed technique based on the alienation coefficient for busbar protection was completed at various cases of fault conditions.

A. Case (1) Normal operation condition at power supply current = 3.8 Amp

Figure 3 shows the test results in case of normal operation condition at load current of 3.8 Amp. The figure presents the measured phase secondary (i_{as1} *and* i_{an1}) and primary currents at the two ends of source and load sides, their cross-correlation (r_1) and alienation coefficient (A_1) and differential current ($i_{ad}(k) = i_{as1}(k) - i_{an1}(k)$) signals.

As expected in normal operation condition, no trip signal is initiated due to cross-correlation coefficient (r_1) between the two current signals of source and load sides is fixed and approximately one; the produced alienation coefficient (A_1) and the differential current signal ($i_{ad}(k)$) between the two current signals are fixed and approximately zero. This information is illustrated in Figure 3.

B. Case (2): Internal SLG (A-G) fault condition through resistance (R_f) = 2.2 Ohm

Figure 4 show the test results in case of internal SLG (A-G) fault through resistance (R_f) = 2.2 ohm. The figure presents the measured phase secondary (i_{as1} *and* i_{an1}) and primary currents at the two ends of source and load sides, their cross-correlation (r_1) and alienation coefficient (A_1) and differential current ($i_{ad}(k) = i_{as1}(k) - i_{an1}(k)$) signals. In this case, it is noticed that the phase secondary current (i_{as1}) at source side during the fault is higher than the secondary current (i_{an1}) at load side as shown in Fig. 4. The calculated cross-correlation coefficient (r_1) is equal and close to unity before fault start and after fault clearance and it is less than r_x (where, $r_x = 0.97$) during fault time as presented in Fig. 4. The calculated alienation coefficient (A_1) is fixed, equal and close to zero before fault start and after fault clearance, and it is greater than A_x (where, $A_x = 0.05$) with fault occurrence. Also, the differential current ($i_{ad}(k)$) increases suddenly with fault occurrence (see Figure 4).

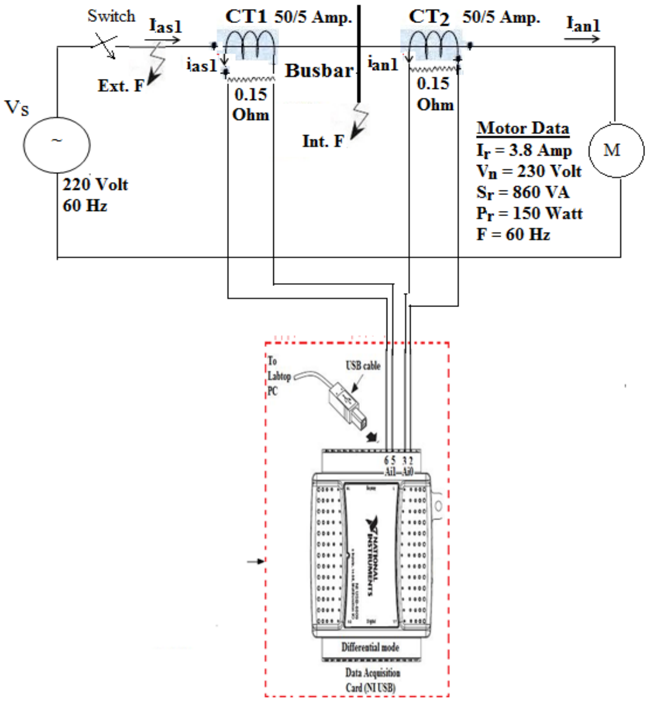

Fig. 2 The Laboratory Circuit for Testing of the Proposed Busbar Differential Protection

C. Case (3) Internal SLG (A-G) fault condition through resistance (R_f) = 0.2 Ohm

The test results of this internal SLG (A-G) fault condition through resistance (R_f) = 0.2 ohm are shown in Figure 5. The figure presents the measured phase secondary (i_{as1} *and* i_{an1}) and primary currents at the two ends of source and load sides, their cross-correlation (r_1) and alienation coefficient (A_1) and the differential current ($i_{ad}(k) = i_{as1}(k) - i_{an1}(k)$) signals. Trip signal is initiated with fault start due to the calculated cross-correlation coefficient (r_1) between the two current signals of source and load sides are less than r_x (where, r_x = 0.97). The obtained alienation coefficient (A_1) between the two current signals is greater than A_x (where, $A_x = 0.05$) with fault occurrence. It is evident clear that the differential current ($i_{ad}(k)$) increases suddenly with fault occurrence (see Figure 5).

D. Case (4) External SLG (A-G) fault condition through resistance (R_f) = 1 Ohm

Figure 6 show the test results in case of external SLG (A-G) fault through resistance (R_f) = 1 Ohm and it is located out of the busbar protection zone at source side. The figure presents the phase primary and secondary current (i_{as1} *and* i_{an1}) signals at the two ends of source and load sides, their cross-correlation and alienation coefficients (r_1 and A_1) and the differential current ($i_{ad}(k) = i_{as1}(k) - i_{an1}(k)$) signal. In this case, it is noticed that the phase secondary currents for source and load sides during the fault are identical and lower than the pre-fault currents as shown in Fig. 6. The calculated cross-correlation coefficient (r_1) is equal and close to unity before, during and after fault occurrence as presented in Fig. 6. The calculated alienation coefficient (A_1) and the differential (i_{ad}) are fixed, equal and close to zero before, during and after fault occurrence (see Figure 6).

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From the shown results, it is clear that the cross-correlation and alienation coefficients are good detectors to determine the internal/external faults. The cross-correlation values are closely to unity for current signals in cases of normal operation and external fault without CT saturation and it is less than one in case of internal fault conditions. Whereas the alienation values are closely to zero for current signals in cases of normal operation and external fault without CT saturation and it is greater than zero in case of internal fault conditions. A trip flag depends on the cross-correlation and alienation values, if their values are less than unity and greater than zero, respectively, then a trip signal is sent for isolation busbar CBs as mentioned in cases "2" and "3" as shown in Figures 4 and 5, respectively. But the two cases "1" and "4" are normal and external fault conditions, respectively, and no tripping signal is issued as shown in Figures 3 and 6, respectively.

E. Case (5) Current Transformer (CT_2) with polarity reverse condition (at load side)

Figure 7 shows the test results in case of normal operation and the current transformer (CT_2), at load side, with polarity reverse condition. The figure presents the measured phase secondary (i_{as1} and i_{an1}) and primary currents at the two ends of source and load sides, their cross-correlation (r_1) and alienation coefficients (A_1) and the differential current (i_{ad}) signal. In this case, the calculated cross-correlation coefficient (r_1) between the two current signals of source and load sides is fixed and close to negative one; the produced alienation coefficient (A_1) is fixed and equal to zero during the testing time. This leads to no trip flag is initiated although the differential current signal (i_{ad}) is increased. This information is illustrated in Figure 7.

V. EXPERIMENTAL RELAY PERFORMANCE

From the obtained results of experimental model, it is clear that the proposed algorithm of busbar differential protection for single phase succeeded in detecting and differentiating between external and internal faults occurring on the busbar zone besides identifying the faulted phase(s). Thus a reliable and efficient technique has been presented for detecting busbar internal and external faults by using cross-correlation and alienation functions. Table (2) illustrates the values of cross-correlation and alienation coefficients for the different fault conditions and the response (action) of the proposed busbar differential protection.

VI. CONCLUSIONS

This paper presents a new proposed algorithm of digital relay for busbar protection. The protection scheme is based on measuring the input and output signals, which are single-phase source-side current and load-side current. The main concept of the suggested technique is based on calculations of cross-correlation and alienation coefficients between the two current signals at the two ends of source and load sides. The coefficient of cross-correlation has upper and lower limits to determine the strength of association for the two variables; its value can vary from positive one, through zero, to negative one. Hence the value of the alienation coefficient can vary from zero to positive one. The performance of the proposed algorithm for protecting busbar is investigated on a physical model of a power system. The physical model is able to emulate the behavior of the actual power plant in the laboratory environment. The suggested digital relay has been implemented on a PC computer. Data acquisition card is used to feed the digital relay by current signals at the two ends of source and load sides. The proposed algorithm has been examined experimentally under different operating conditions for various types of internal and external faults. The test results obtained from the experimental tests verify a reliable and efficient technique for detection and discrimination between busbar internal and external faults by using cross-correlation and alienation functions.

REFERENCES

[1] IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes IEEE Std. C 37.110-1996.

[2] Working group of the Relay Input Sources Subcommittee of the Power System Relaying Committee "Transient response of current transformers" IEEE Transaction on power apparatus and systems, Vol. PAS-96, no. 6, November/December 1977.

[3] W.J. Smolinky "Design Consideration in the Application of Current Transformers For Protective Relaying Purposes", IEEE Transactions on Power Apparatus and System, Vol. PAS-92, no.4, July/August 1973.

[4] D.A. Bradley, C.B.Gray, D.O'Kelly "Transient compensation of current transformers" IEEE Transactions on Power Apparatus and Systems, Vol. PAS-97, no.4, July/Aug 1978

[5] Y.C. Kang, J.K.Park, S.H.Kang, A.T. Johns, R.K. Aggarawal " An algorithm for compensating secondary currents of current transformers" IEEE Transactions on Power Delivery, Vol.12, no.1, January 1997

[6] D.C.Yu,Z.Wang, J.C. Cummins,H.-J. Yoon,L.A.Kojovic,and D.Stone "Neural network for current transformer saturation correction" in proc. IEEE Transm. Distrib. Conf., New Orrleans,LA,Apr.1999.

[7] M.E. Masoud, E.H.Shehab-Eldin, M.M Eissa, and M.F.Elnagar. "A New Compensating secondary current technique for saturated current transformers" The 8thInternational Middle- East power system conference "MEPECON 2001", PP549-555.

[8] Jiuping Pan, Khoi Vu, and Yi Hu "An Efficient Compensation Algorithm for Current Transformer Saturation Effects" IEEE Transactions on Power delivery, Vol. 19, no.4, October, 2004, PP1623-1628.

[9] M.A. Salem, M.I. Gilany,Z. Osman and E. aboul Zahab " A new algorithm for compensating the secondary current during current transformer saturation" The tenth International Middle- East power systems conference "MEPECON 2005" PP 427-433.

[10] M.S. Sachdev, T.S. Sidhu, H.S. Gill, "A busbar protection technique and its performance during CT saturation and CT ratio-mismatch", Power Delivery, IEEE Transactions on (Volume:15, Issue: 3), Page(s):895 - 901, Jul 2000.

[11] Xuyang Deng, Jiale Suonan, Zaibin Jiao and Xiaoning Kang, "A Model Parameter Identification Based Bus-bar Protection Principle", Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific, Page(s):1 – 6, March 2010.

[12] Jiale Suonan, Xuyang Deng and Guobing Song, "A Novel Busbar Protection Based on Fault Component Integrated Impedance", Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific, Page(s):1 – 6, March 2010.

[13] Libao Xu, Grasset, H., Xingli Dong, Chenliang Xu and Ruidong Xu, "A new method for busbar protection stability improvement", Developments in Power System Protection (DPSP 2010). Managing the Change, 10th IET International Conference on, Page(s):1-4, April 2010.

[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] Labview 8.5, (Labview professional development system), NI.com/Labview.

[16] 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.

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[17] 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.
[18] Press, W. H.; Flannery, B. P.; Teukolsky, S. A.; and Vetterling, W. T. "Linear Correlation", Cambridge, England: Cambridge University Press, pp. 630-633, 1992.
[19] 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.

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4. EXPERIMENTAL RESULTS AND TECHNIQUE EVALUATION BASED ON CORRELATION FOR GENERATOR STATOR FAULT DETECTION (Power Systems Conference, 2012, MEPCON 2012).

TABLE (1) *Alienation* coefficient ranges at different fault conditions for the protected busbar.

Fault Type	*Alienation Coefficients* $A_x = 0.05$	*Relay Action*
1.Normal (healthy) condition	$A_a \le A_x$, $A_b \le A_x$ and $A_c \le A_x$	*Blocking*
2. External fault condition (without CT saturation)	$A_a \le A_x$, $A_b \le A_x$ and $A_c \le A_x$	*Blocking*
3. internal fault condition	$A_a > A_x$, $A_b > A_x$ or $A_c > A_x$	*Tripping*
4. External fault condition (with CT saturation)	$A_a \le A_x$, $A_b \le A_x$ and $A_c \le A_x$ *(During the first quarter-cycle after fault detection, i.e. free saturated portion of secondary current signals)*	*Blocking*

Table (2) Cross-correlation and alienation coefficients values in cases of different fault conditions and the response of proposed digital relay for busbar protection.

Busbar condition	*Cross-correlation*(r_1) $r_x = 0.97$	*Alienation* (A_1) $A_x = 0.05$	*Relay action*
1. Normal operation	$1 (r_1 \ge r_x)$ *For each phase*	$0 (A_1 \le A_x)$*For each phase*	*Blocking*
2. Internal fault	$A_1 < r_x$ *at least one phase*	$A_1 > A_x$ *at least one phase*	*Tripping*
3. External fault without CTs saturation	$1 (r_1 \ge r_x)$ *For each phase*	$0 (A_1 \le A_x)$ *For each phase*	*Blocking*
4. Two CTs Reverse polarity	*-1*	$0 (A_1 \le A_x)$ *For each phase*	*Blocking*

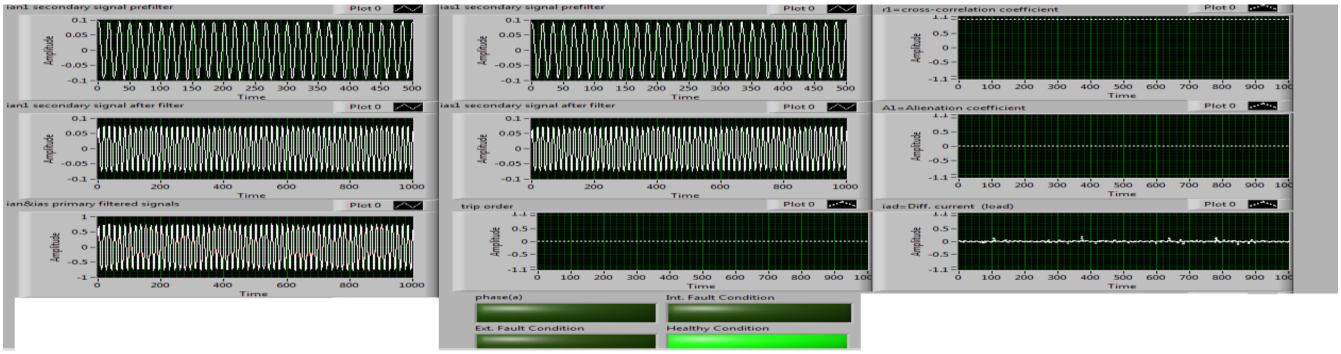

Figure 3. Test Results for Case 1 (Normal Operation)

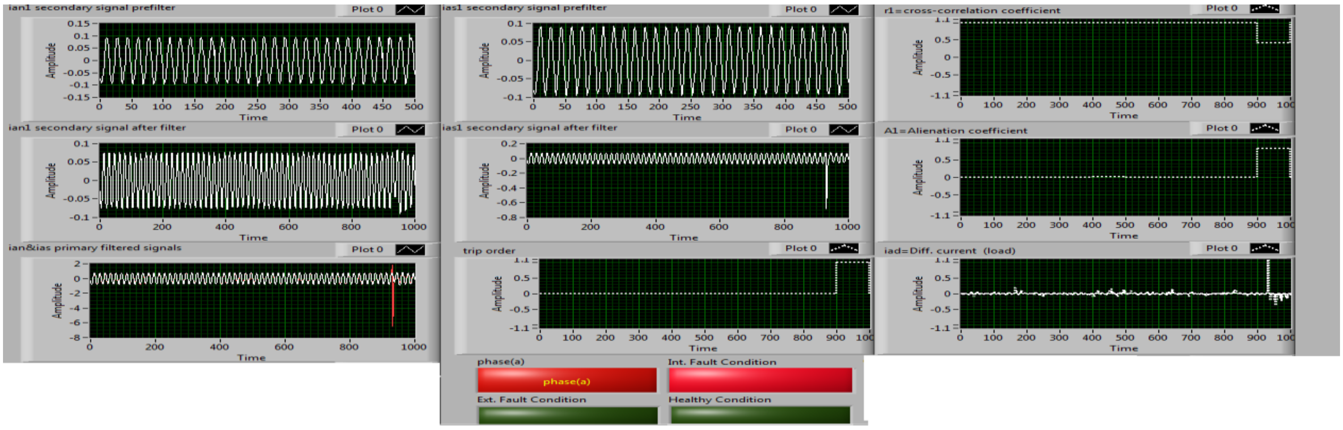

Figure 4. Test Results for Case 2

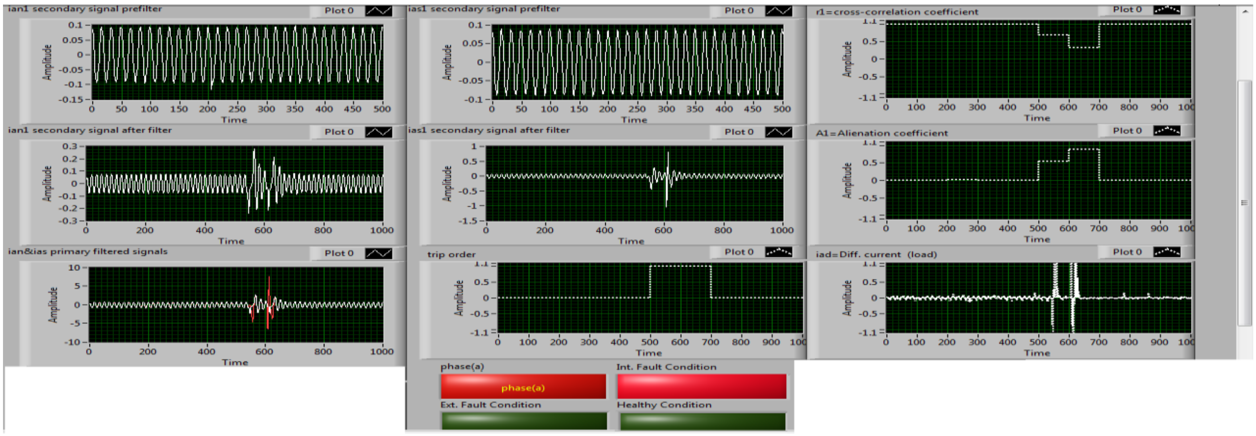

Figure 5 Test Results for Case 3

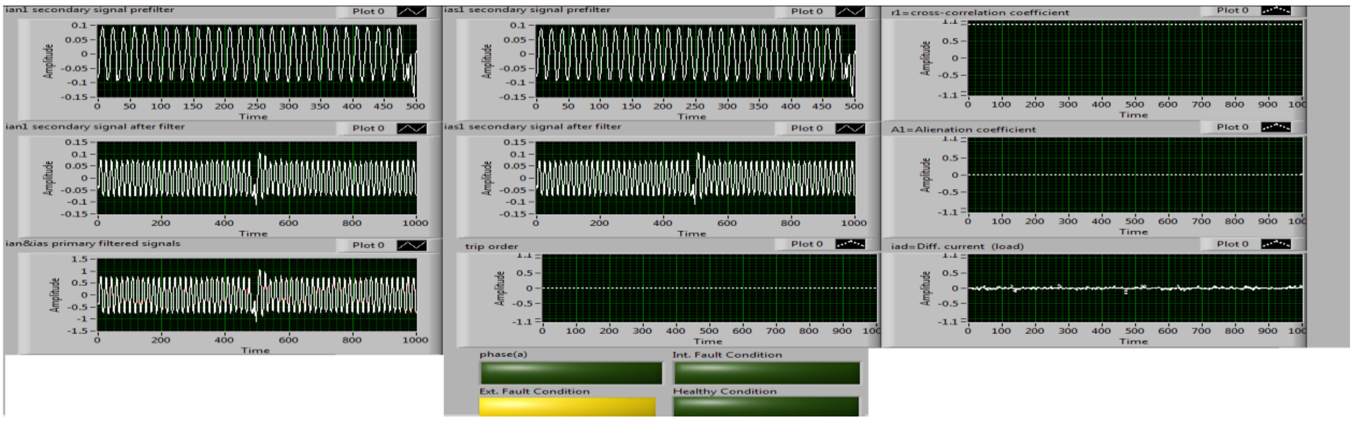

Figure 6 Test Results for Case 4

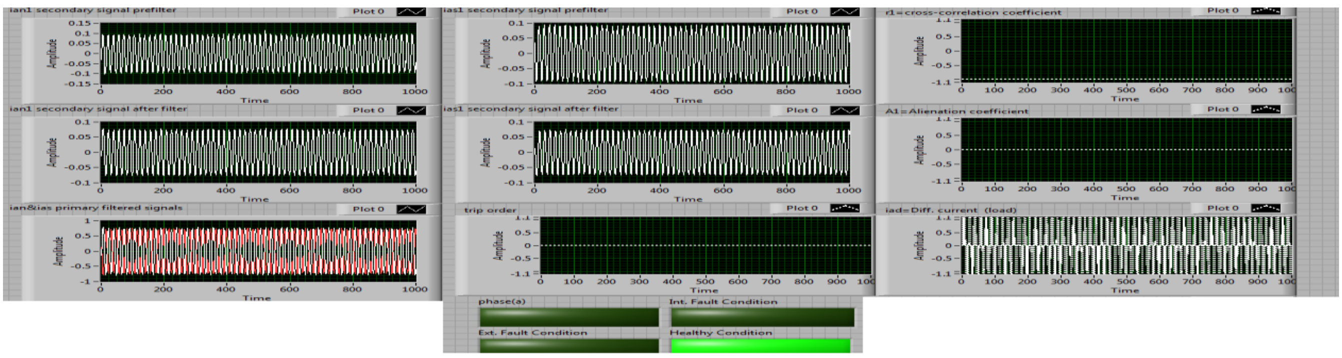

Figure 7 Test Results for Case 5

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