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Optimal Protection Scheme for Distribution Systems Integrated with Distributed Generators

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ABSTRACT

Combination between the distributed generator (DG) such as conventional distribution grid, tidal turbines, and nuclear power plant is increasing rapidly around the countries, because of its reliable and nature- friendly behaviors. Also, DGs are a major feature in a smart grid. However, this integration causes bidirectional current flows and contributes to the level of fault current especially during the power swing. Therefore, it changes the fault current pattern in the distribution network and adversely affects the coordination of the protection relays. Many papers have proposed different techniques to detect and classify the faults in distribution network and only isolate the faulty section such as (protection coordination using dual setting directional relays, Fuzzy logic based method, wavelet transform based method, Adaptive protection based techniques...etc). In the light of this situation, a comprehensive protection algorithm is proposed in this paper to detect any fault in distribution network with DGs during the power swing and guarantees a secure and reliable performance to avoid any unintentional disconnection during any fault case. The proposed protection direction scheme totally depends on the auto regression technique for the positive sequence component of currents angles difference (fault–prefault). It is better to depend on current signals only in designing smart protection systems. In this article, a proposed protection scheme depending on current signal of two terminals. The effectiveness of the proposed scheme is demonstrated compared to other methods in the literature

I. INTRODUCTION

The necessity for smart grid systems having minimum electrical loss and environmental impact, therefore, The electric power system planners are providing the full support to go for Distributed Generations (DGs) which have several other advantages such as reduced transmission and distribution system resources, increased reliability of the grid, offered better power quality. However, this system is subjected to several power swings more than the conventional system, and as the number of distributed generators is increased, the probability of occurrence of power swing is also increased [1]. During power swing, the distance relays are blocked from operation because the apparent impedance calculated by distance relay may be inside its tripping zones. If a fault occurs during the power swing, the distance relay must operate to isolate the faulty part. However, the calculated fault impedance during the power swing is not accurate because the analog inputs are slipped form its fundamental frequencies [2]. Also, in some fault cases, the voltage polarization approach becomes unreliable especially when the fault occurred at the lowest voltage value during the power swing [3].

Recently, numerous researches have been proposed to detect the faulty part in the smart grid [4-6]. In [4], presented a technique depends on the travelling waves generated by the fault, also address drawbacks of the conventional schemes. A method based on wavelet transformation of fault currents is proposed in [5]. In [6] presented technique depends on finite state automata (FSA) and positive-sequence components (PSC) to determine the fault point in transmission line. The line current differential protection relay becomes increasingly more attractive in smart grid power systems

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due to its hardly affected by changing system conditions. However, line current differential protection requires along-haul communications channel to share current data between two relays, as well as a comprehensive synchronization algorism with special communication links to compensate the current values measured at two line terminals [7]. In [8], presented technique depends on discrete wavelet transform to detect and classify faults for Multi-terminal Transmission Line with Nuclear Power Plant. In addition, the nuclear power plants planned will be integrated with the Egypt electric network in 2026. In [9] presented technique depends on Decision tree to detect and classify faults for a Thyristor Controlled Series Capacitor (TCSC) compensated line during power swing. In [10] presented Statistical approach based on signal energy for detect and classify fault and unstable and stable power swings.

This paper proposes an improved scheme of fault detection and classification for transmission lines by monitoring the rate of change of the power flow direction using only current signals without voltage signals. The methodology of fault directional identification used in this paper is totally depends on the auto regression technique for the positive sequence component of currents angles difference (fault–prefault). It is better to depend on current signals only in designing smart protection system. In this article, a proposed protection scheme depends on current signal of two terminal is used for detecting the fault.

This paper is organized as follows: Section 1 describes the recent techniques for fault detection and classification for TL during power swing. Section 2 presents the main features of the proposed scheme. Section 3 presents the system under study, simulation and results for various fault types, locations, inception angles and fault resistance. Section 4 is dedicated to conclusions and future works.

II. PROPOSED SCHEME DESCRIPTION

In [11], a conventional method based on two directional overcurrent relays is introduced for fault detection. As shown in fig.1, the fault F1 is detected in the protected line2 if the fault direction seen by two terminal relays (R1&R2) is forward. This method uses the voltage signals in defining the fault directionality, therefore, it is hardly to define the voltage polarization approach especially when the fault occurred during power swing is too close proximity to the relay point and the relay is fully grounded by the short circuit current, typically called as ‘close-in’ fault [12].

The proposed scheme can detect the fault during the power swing by monitoring the rate of change of the power flow direction using only current signals without voltage signals. The methodology of fault directional identification used in this paper is totally depends on the auto regression technique for the positive sequence component of currents angles difference (fault–prefault).

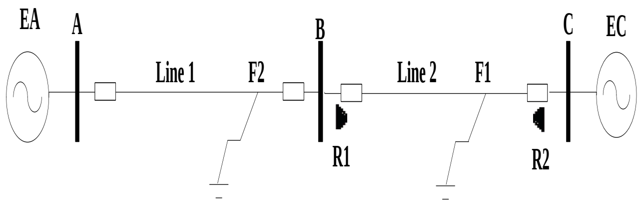


Fig. (1): 22 KV Simulated System

Current –only fault directional principle

The directional relay technique used will illustrate in this section. Fig.1 shows 3-buses with 22-kV system. Source A is equivalent to utility-grid and source C is equivalent to a collection of DG units, which refer to a micro grid. When the fault occurs on the F1 point, the angle difference between the positive sequence component of pre fault current (I_{L1}) and the fault current seen by the relay at bus B (I_{F1}) is given by the following equation [13]:

$$Ang_\theta = arg\frac{I_{F1}}{I_{L1}} = arg\frac{E_{A1}-U_{F1}}{Z_{A1}+Z_{AB1}}$$

Where: E_{A1} is the positive component of source A, and U_{F1} is the positive voltage component of bus B after the fault. Z_{A1} and Z_{AB1} are the positive sequence impedance of equivalent source A and line 1 respectively.

The angle of line impendence is hardly affected with the line length; so that, arg (Z_{A1}+Z_{AB1}) ε (0◦, 90◦).

According to the voltage characteristic after the fault, the positive voltage component is measured by the healthy-phase. Hence, the phase angle for positive component of the voltage on the busbar B after the fault is the same as the phase angle prior the fault; so that arg (E_{A1}-U_{F1}) ε (-90◦, 90◦) and thus;

Ang_θ ε (180◦, 360◦) or Ang_θ ε (-180◦, 0◦).

The same mathematical analysis is used for fault at the F2 point. Thus, the phase angle difference is Ang_θ ε (0, 180). In another words, the change in the power flow can be detected by the changing the value of Ang_θ .

During power swing the value of angle difference is deviated from the above equations, and most cases of power swing the degree of deviation is significant. The problem is that, the power swings have a lot of cases and hundreds of potential slip frequencies. Thus, an auto adaptive mechanism is needed to predict the deviation value and tuning the protective algorithm.

In this paper, an auto regression technique is used to tackle the changing in Ang_{θ} value and accurate detect the fault direction.

Auto regression technique [14] is an especial method for regression digital signals analysis. It models the *n*th value of a variable as a function of *k* previous data, where *k* is the regression order. The accuracy of the prediction points depends on the value of *k*. The full discrete form for the auto regression model is given by:

$$i_n = a_0 + a_1 i_{n-1} + a_2 i_{n-2} + \cdots + a_k i_{n-k} \quad \textbf{(1)}$$

Where: $a_0, a_1, a_2, \ldots\ldots, a_K$ are the regression coefficients and *i*'s are the variable samples. These coefficients are calculated by using a set of *p* available sampled points. The value of *p* should be selected much higher than *k* for accurate calculation of future sampled data.

The previous equation can be expressed in matrix form as follows,

$$\begin{bmatrix} i_n \\ i_{n-1} \\ \vdots \\ i_{n-p} \end{bmatrix} = \begin{bmatrix} 1 & i_{n-1} & \cdots & i_{n-k} \\ 1 & i_{n-2} & \cdots & i_{n-1-k} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & i_{n-p-1} & \cdots & i_{n-p-k} \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_k \end{bmatrix} \quad \textbf{(2)}$$

For simplifying, it can be re-written as:

$$[C] = [B][A] \quad \textbf{(3)}$$

The unknown coefficients vector [A] is calculated using the least-square technique:

$$[A] = [B]^{+}[C] \quad \textbf{(4)}$$

Where: [B] + is the pseudo inverse of [B].

The future sampled data are predicted by using available samples and calculated regression coefficients:

$$i_{n+1} = a_0 + a_1 i_n + a_2 i_{n-1} + \cdots + a_k i_{n-k+1} \quad \textbf{(5)}$$

The next *x* samples can be obtained using Eq. (5). If the prediction length is too large, the accuracy of the technique becomes slowly and vice versa. Therefore, the tuning value of *x* is required and, in this study, it is chosen referring to the number of samples per power frequency cycle. The accuracy of the prediction technique depends on the selection values of *k*, *p* and *x*. Based on different power swing studies for different systems, it is optimum to take *k*=40. As mentioned, *k* should have a value less than *p* for best estimation of regression coefficients. In this study, *p*=128 is chosen which improves the accuracy in predicting the future data.

If the direction of power flow after fault is not changed prior to the fault, the difference between the predicted and actual values of the Ang_{θ} is too much less than the threshold value; otherwise, the difference is significant. The threshold value has a wide range of correct values and can be easily selected because if there is no change in the power flow direction, the proposed method gives a value approximately equal to zero under all fault cases for all power swing types; and vice versa.

Proposed Scheme Structure

The flow chart and the logic diagram of the proposed scheme are shown in fig 2 and 3 respectively. Once the power swing is activated, the proposed scheme is enabled and only current signals are used to detect the fault.

The positive sequence component of current signals angles difference (fault–prefault) is continuously computed as vector data. Then, the auto regression technique uses this vector data to detect the rate of change of power flow. The outputs of auto regression are either 1 or 0. The output is 1 in case of the auto regression measured value greater than the threshold value; and vice versa.

The designed logic scheme shown in fig. 3 captures the updated auto regression value from two ends of the protected line as an input value (I/P 1, and I/P 2) and release the final decision. The results of the proposed logic scheme takes the form of 1, and 0; which means that the fault within and without the protective line, respectively.

The fault is detected within the protected line only if the auto regression outputs of two ends relays are not equal. For example, from fig.1 assume the fault in the protected line 2 and the power flows from bus A to bus C. The outputs of the protective relays R1 and R2 will be 0, 1 respectively. But, if the power flow direction is reversed (from bus C to bus A) prior to the fault occurrence, the outputs of relays R1 and R2 will be 1, 0 respectively.

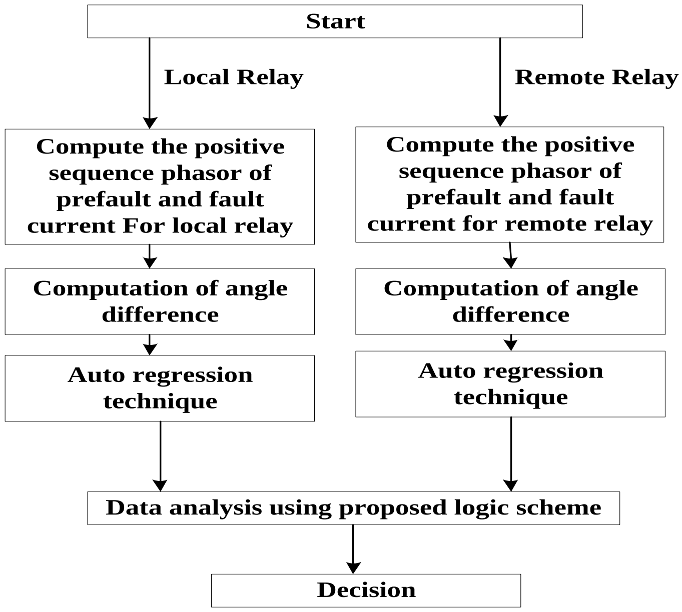


Fig. (2): Flowchart for the proposed scheme

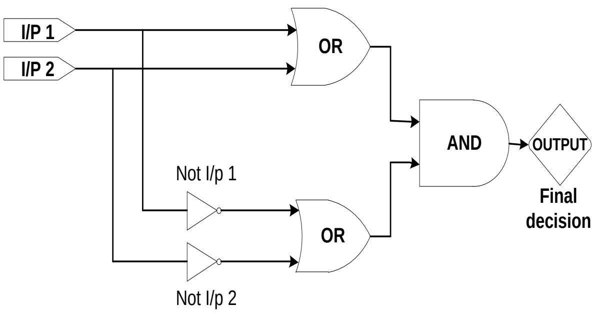


Fig. (3): Logic diagram of the proposed scheme

III. SIMULATION RESULTS

The simulated case study is shown in Fig. 4, which consists of two main sources. Source A is modeling a micro 66 kV smart grid, ZA is equivalent source impedance, Tr1 is a step up transformer, and source C is a collection of 22 KV DG units G. All related parameters of this studied system, which simulated by ATP software are given in appendix A. The transmission Line 2 is protected by the proposed scheme using two terminal relays B and C. The two relays share the information data between each other using any communication links like fiber cable or PLC. To demonstrate the effectiveness of the proposed algorithm, the power swings is simulated with different slip frequencies in the range of 1–5 Hz. To create different cases of power swing with different slip frequencies, the frequency of source A is kept constant at 50 Hz, while the frequency of source C is deviated from the fundamental frequency.

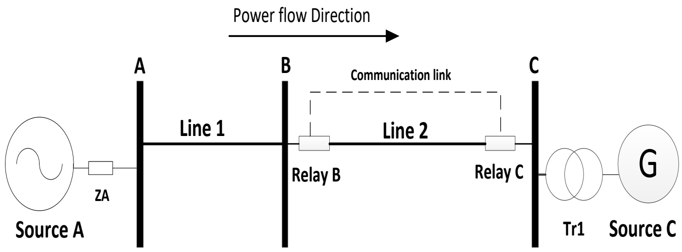


Fig. (4): Simulated 66 KV System

The proposed scheme is well tested under several kind of fault (symmetrical and unsymmetrical faults) at different fault instants during different power swing conditions. Also, the effect of the nonlinearity of arc fault resistance is examined in this study. The arc fault model used in this paper is fully based on the theory of the arc column energy balance as in the Appendix B [15].

The whole process is based on a moving window approach where the one-cycle window is moved continuously by one sample as shown in fig. 5.

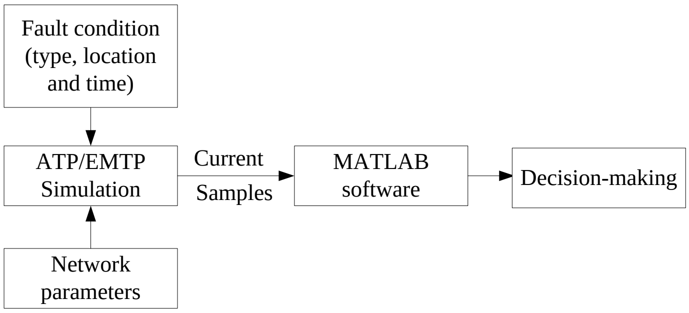
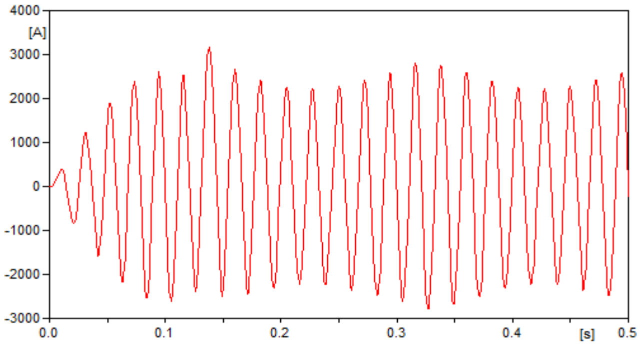
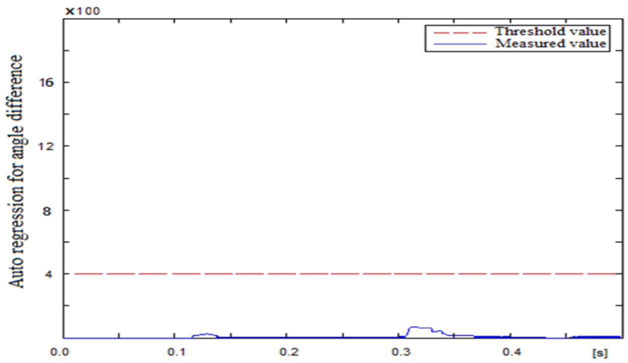


Fig. (5): The fault patterns process

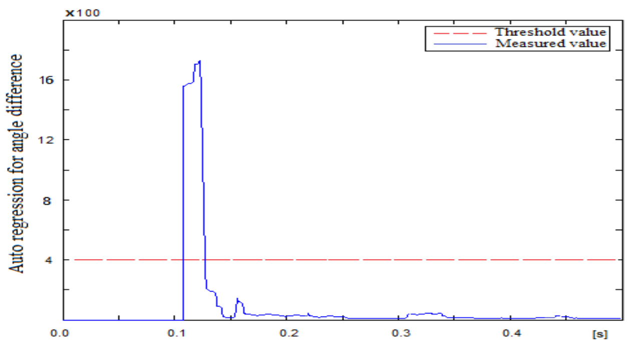
Fig. 6 depicts the waveforms of phase-A current measured by relay B, and the proposed algorithm performance under single phase fault during fast swing with slip frequency equal to 4 HZ. The fault is occurred at 40 km from bus B which corresponds to 70% of line 2 length with an arc fault length of 200 cm. For local relay B shown in fig. 6 (b), the auto regression measured value is much less the threshold value this is because the fault direction is the same as the power flow direction prior to the fault, thus, I/P1 =0. According to remote relay C shown in fig. 6 (c), the fault current direction is opposite to pre-fault current direction, therefore, I/P2 =1. Because the two inputs are not the same, the output of the logic protection is one and this means, the fault within the protected line 2. The fault is initiated at 0.1 sec and cleared after one power cycle (20 ms).



(a) Current waveform of phase A

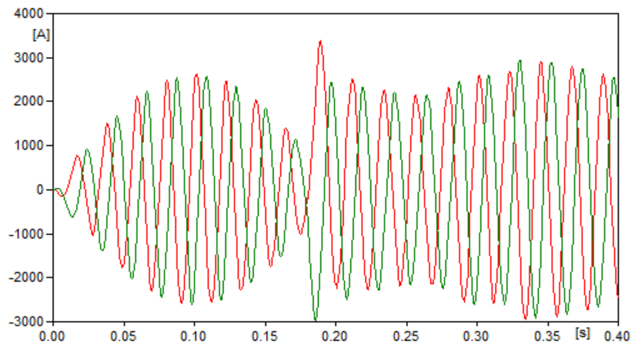


(b) Local relay respond

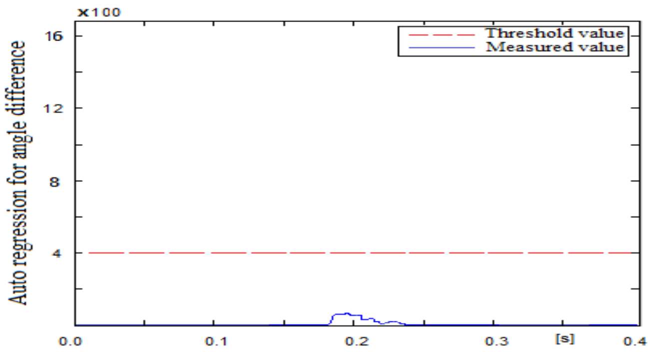


(c) Remote relay respond

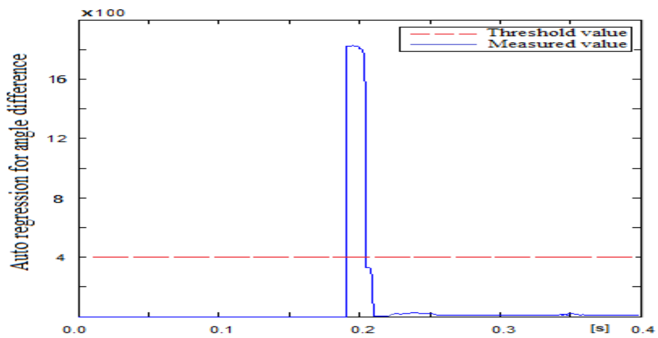
Fig. (6): Current, and proposed method behavior during A-G internal fault



(a) Current waveform of phase A-B



(b) Local relay respond



(c)Remote relay respond

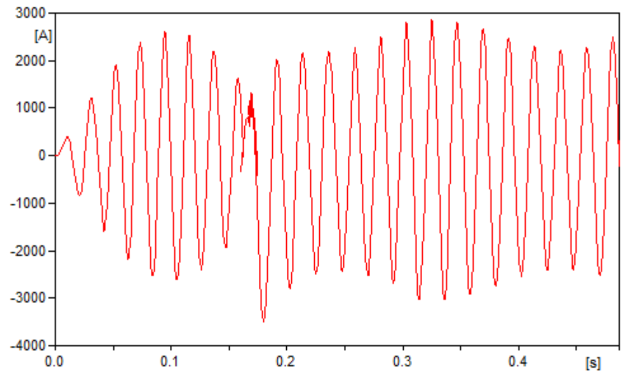
Fig. (7): Current, and proposed method behavior during A-B internal fault

As shown in Fig. 7, a two-phase internal fault between phase A and B is initiated at 0.181 sec during fast swing with a slip frequency of 5 Hz. The fault location is about 20 km from the bus B and the arc length is 150 cm. The proposed method can detect this fault at 0.195 sec (less than one cycle). Moreover, in Fig. 8, a single-phase external fault in line 1with arc length of 100 cm is initiated at 0.13 sec. The fault is created at 40 km from the bus A during fast swing with a slip frequency of 4 Hz. As shown from Fig. 8 (b) &(c), the two inputs (I/P1, and I/P2) are active high due to the fault current direction is opposite to the pre_fault current direction. According to the proposed logic diagram shown in Fig. 3, the final decision will be active low and this means the fault is outside the protected zone and no trip signal generated for line2.

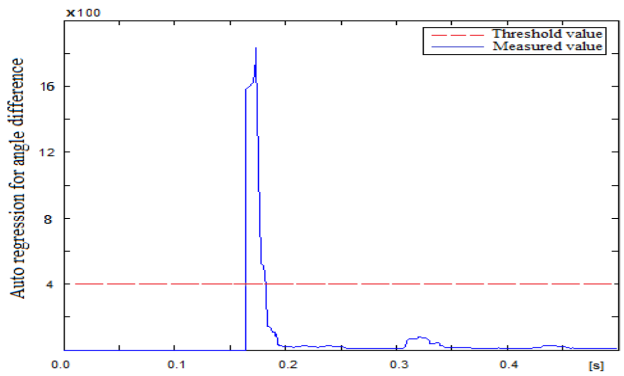
Table 1 concluded the performance of the proposed schemes during several fault conditions under differing swing cases. All fault kinds in this table are initiated with several arc fault length (90cm, 150cm and 200cm) under different swing conditions (slip frequencies: 1 Hz, 2 Hz, 3 Hz, 4Hz, and 5 Hz). The proposed method gives the same performance for all fault cases, therefore, it's satisfactory to only present the results in table 1 for different fault types with arc length equals to 150 cm and 4 Hz of swing slip frequency. In this table, forward means the power flows from bus A to bus B prior to the fault occurrence, and vice versa. Also internal fault means the fault in the protected zone (line 2) and reverse means the fault in line 1. It can be seen that the proposed scheme has a superior performance and can effectively detect all fault types in the protected zone and never give mal operation for external fault.

Table (1): PROPOSED SCHEME BEHAVIOR DURING SEVERAL FAULTS

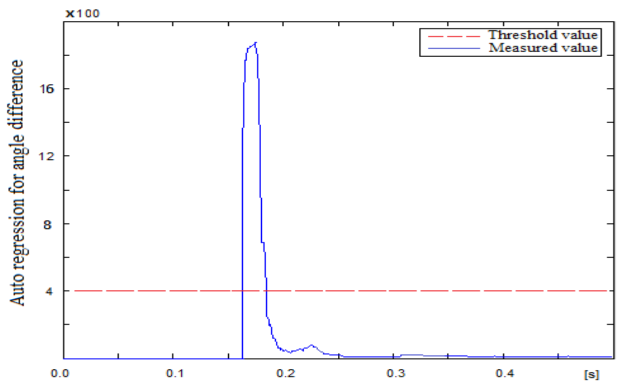
Fault type	Fault location	Power flow direction prior to fault	Proposed scheme behavior		
			Local relay	Remote relay	Final decision
Ph-G	External	Forward	I/P1=1	I/P2=1	No Trip
Ph-Ph	Internal	Forward	I/P1=0	I/P2=1	Trip
Ph-Ph-G	External	Forward	I/P1=1	I/P2=1	No Trip
3-Ph	External	Forward	I/P1=1	I/P2=1	No Trip
Ph-G	Internal	Reverse	I/P1=1	I/P2=0	Trip
Ph-Ph	External	Reverse	I/P1=0	I/P2=0	No Trip
Ph-Ph-G	Internal	Reverse	I/P1=1	I/P2=0	Trip
3-Ph	Internal	Reverse	I/P1=1	I/P2=0	Trip



(a) Current waveform of phase A



(b) Local relay respond



(c)Remote relay respond

Fig. (8): Current, and proposed method behavior during A-G external fault

IV. CONCLUSIONS

In this paper, a proposed scheme is presented for detecting fault in transmission system during any stable and unstable power swing condition. This scheme is based on analyzing the rate of change of positive sequence current angle between two ends of the protected transmission system. The effectiveness of test results is proved by plenty of ATP simulations. The proposed scheme possesses several outstanding advantages over the traditional relays as follows:

- High speed, as the proposed algorithm can detect any fault at time less than one power cycle and immune to the fault type, fault arc, power flow direction, and swing conditions.
- Easy to adaptive the relay parameter settings, as its threshold value is not sensitive or critical.
- Simple teleprotection scheme, the two terminals relays share only one single data, therefore, only one digital channel and any communication link (like; power line carrier or fiber cable) are needed.
- Optimal solution for smart grid, as it doesn't depend on the configuration of the power system, therefore, it is not required to reconfigure the protective relays during adding additional generator in the power system.
- Optimal solution for close-in fault case, as the proposed theory doesn't depend on the voltage signals.

Finally, we should point out that other factors that were beyond the framework of the study, and will be included in future studies, are considering the power quality issues and studying the behavior of the proposed scheme in case of single pole tripping.

APPENDIX A

The parameters of the simulated system are as follows:

- Equivalent Generator G: 600 MVA, 22 kV, 50 Hz,

  X_d= 1.72 p.u., X'_d= 0.29 p.u., X''_d = 0.24 p.u., T′do = 8 s, T''_{do} = 0.03 s, X_q = 1.8 p.u., X''_q= 0.26 p.u., T''_{qo} = 0.03 s,

  R_a = 0.004 p.u., X_p =0.14 p.u.
- Transformar : 22/66 kV, 50 Hz, Yn/Yn
- Equivalent source impedance:

  Z_{A1}=0.54+j6.9 (Ω), Z_{A0}=1.2+j10.9 (Ω)
- Transmission line parameters:

  Z_1 = 0.10 + j0.9 Ω/km, Zo = 0.31 + j1.299 Ω/km

  $C_1 = 1.007 \times 10^{-8}$ F/km, Length=60 km

APPENDIX B

ARC FAULT MODALING

The arc model is described in air by the following differential equation: $\frac{dg}{dt} = \frac{1}{\tau}$(G-g)

Where τ: is the arc time constant, g is the instantaneous arc conductance, which can be evaluated by:

$G = \frac{|i_{arc}|}{u_{st}}$, $U_s = U_1 + r_1 * |i_{arc}|$

Where: i_{arc} is the instantaneous arc current, U_s is the stationary arc voltage, U_1 is the characteristic arc voltage, r_1 is the characteristic arc resistance. Variable U_1 and r_1 are dependent on arc length (l_a), and calculated by the following equations:

$$U_1 = 0.9\frac{KV}{m} * l_a + 0.4\,kV,\ r_1 = 40\frac{m\Omega}{m} * l_{arc} + 8\,m\Omega$$

For the fault current in range from 1.4kA to 24kA, the time constant τ can be determined by: $\tau = \frac{\alpha * I_{fP}}{l_a}$

Where the coefficient α is equal to 2.85 ×10E-5 and I_{fP} is the arc peak fault current.

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