DISTANCE RELAY PERFORMANCE DURING SINGLE-POLE TRIPPING AND POWER SWING CONDITION

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Abstract

Power swing enters the power system network due to various disturbances such as fault, application and removal of large load, loss of generation and switching of a transmission line etc. Generally, it is assumed that power swing is the symmetrical phenomenon which imposes an identical effect on three-phase currents and voltages of a power system. Therefore most of the literature surveys are carried out to study the symmetrical power swing and its impact on the performance of distance relay. Nonetheless, there is another type of power swing which is asymmetrical in nature. It enters into the power system when single-pole tripping is performed in a long transmission line which is heavily loaded. The consequence of this type of power swing on distance protection is widely studied in this paper. The undesired operation of distance relay owing to the existence of zero sequence current under asymmetrical power swing is restrained by using a proposed earth fault detection algorithm. The proposed algorithm and effect of single-pole tripping on distance relay is analyzed using the two test systems.

Keywords: Transmission line, single-pole tripping, distance protection, asymmetrical power swing.

I. Introduction

The power system operates very near to its nominal system frequency under steady-state conditions. During the power system's normal operating state, there is a balance between power generated and the load power demand. Also, the variation of sending end and receiving end voltage is within 5%. The various abnormalities in the power system such as loss of generation, faults, transmission line switching and switching of large loads, etc. create oscillations in the synchronous machine rotor angle. This problem further causes the oscillation in transferred power, and finally, the resulting phenomenon is termed as power swing. Depending upon the severity of disturbance, the ensuing power swing is stable or unstable [1]. The large power swing may be stable or unstable, which causes the unwanted tripping of the distance relay. This problem further leads to cascading tripping and power blackout [2]. Distance protection in transmission and meshed distribution network provides reliable protection [3]. During the fault and power swing condition, the impedance calculated by distance relay enters into its operating zone. Therefore distance relay is not able to distinguish the power swing and fault. To solve this problem, the power swing blocking (PSB) feature is incorporated in the distance relay. The primary function of PSB is to detect the power swing and restrict the operation of distance relay during a power swing condition. The operating principle of PSB depends upon the rate of variation of impedance with time under power swing and fault condition.

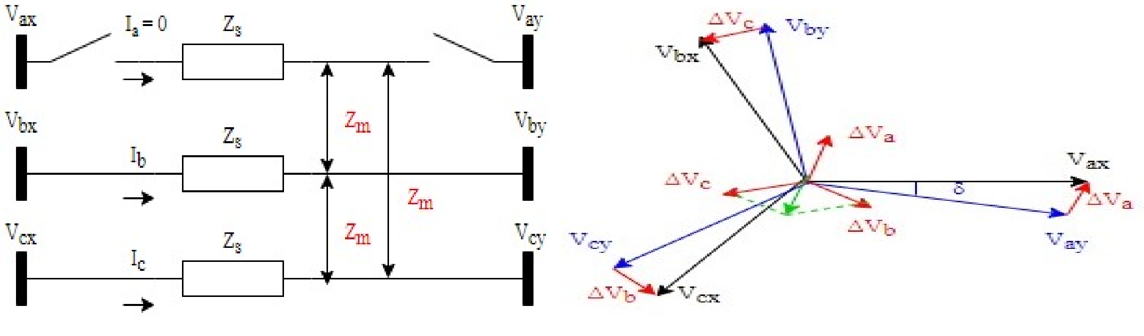
The power system is under stressed condition during power swing. If a fault or any other disturbance happens under this situation, major oscillations the system will experience could also endanger the entire system stability. Some distance relays use a zero-sequence current to distinguish the fault and power swing [4]. However, this approach is not sufficient during symmetrical power swing. The three-phase fault detected during power swing in [5] by observing the energy content in high-frequency components of forward and backward traveling waves. The wavelet transform is able to divide the signal into a different frequency range. This ability is used in [6] to differentiate the fault and power swing.

In the present day, the fault under power swing is detected by using artificial intelligent technique [7], but the method requires more time in the training procedure. The wavelet singular entropy is calculated in [8] to distinguish the power swing and fault, but the sampling frequency used in this method exceeds the available numerical based distance relay. In some numerical distance relays, the impedance calculation is dependent on the pharos estimation of voltage and current [9]. Distinction of Symmetrical fault from power swing is achieved in [10] by using the transient changes in dynamic vector.

Single-pole tripping (SPT) and single-pole reclosing (SPR) is common procedure for improving the transient stability of a power system. Asymmetrical power swing enters into the power system when SPT is performed in a long transmission line which is heavily loaded [1], [11], [12]. Therefore there is an undesired distance relay operation owing to the existence of earth current under asymmetrical power swing [13]. To solve this problem, the PSB function should detect the fault and power swing on each phase individually [14]. The consequence of SPT on distance relay studied in section II. The impact of asymmetrical power swing on distance relay carried out in section III. After that, the earth fault detection algorithm and simulation results are studied in section IV and V respectively.

II. Consequence of SPT on Distance Relay

To protect the transmission line from symmetrical and unsymmetrical types of fault, the distance relay integrated with six distance protection units, consisting of three phase units and three ground units. During SPT of phase *a* of transmission line shown in Fig. 1(a), the magnitude of voltage and current of each phase is different, which may cause the undesired operation of the protection system. Before examining the effect of SPT on distance protection, the healthy phases current during the SPT condition are extracted as:



(a) (b)

Figure 1: *Evaluation of 3-phase transmission line under the SPT of faulted phase a: (a) SPT of phase a; (b) vector diagram of voltage.*

I. Healthy Phases Currents during SPT

To find the healthy phases currents during SPT situation consider Fig. 1(a). During SPT of phase a, the following equation can be written as:

$$V_{bx} - V_{by} = Z_s I_b + Z_m I_c \ , V_{cx} - V_{cy} = Z_s I_c + Z_m I_b \tag{1}$$

Where, Zm and Zs are the mutual impedance and self-impedances of the transmission line, respectively. Consider the transmission line is to be transposed, the zero sequence and positive sequence impedances of the line are Z_0 =Zs+2 Zm and Z1= Zs - Zm.

The earth current I_E during the SPT condition is given by the following equation:

$$I_E = 3I_0 = I_a + I_b + I_c = I_b + I_c \tag{2}$$

Using (2), the (1) can be written as:

$$\triangle V_b = (Z_s - Z_m)I_b + Z_m I_E, \triangle V_c = (Z_s - Z_m)I_c + Z_m I_E \tag{3}$$

With the help of K_0 define in (4); the healthy phase currents are obtained as:

$$K_0 = \frac{Z_m}{Z_1} = \frac{Z_0 - Z_1}{3Z_1} \tag{4}$$

$$I_b = \frac{\triangle V_b}{Z_1} - K_0 I_E, I_c = \frac{\triangle V_c}{Z_1} - K_0 I_E \tag{5}$$

Currents are expressed in terms of voltage difference using (2) and (5)

$$\begin{cases} I_b = \left(\frac{1+K_0}{1+2\,K_0}\right)\frac{\triangle V_b}{Z_1} - \left(\frac{K_0}{1+2\,K_0}\right)\frac{\triangle V_c}{Z_1} \\ I_c = \left(\frac{1+K_0}{1+2\,K_0}\right)\frac{\triangle V_c}{Z_1} - \left(\frac{K_0}{1+2\,K_0}\right)\frac{\triangle V_b}{Z_1} \end{cases} \tag{6}$$

Form (2) and (6), I_E is expressed as:

$$I_E = \frac{1}{Z_1}\left(\frac{1}{1+2\,K_0}\right)(\triangle V_b + \triangle V_c) \tag{7}$$

Assuming that magnitudes of the voltages at buses x and y are same and separated by an angle, δ the per phase voltage is given by

$$\triangle V = |V|\angle 0 - |V|\angle - \delta \tag{8}$$

The phase a is taken as reference and $\alpha = 120\ \angle 0^0$

$$\triangle V_b + \triangle V_c = \left(\alpha^2 + \alpha\right) \triangle V = - \triangle V \tag{9}$$

The healthy phase's currents before the SPT are given as follows:

$$\begin{cases} I_{b,ini} = \frac{\triangle V_b}{Z_1} = \frac{\alpha^2 \triangle V}{Z_1} = \alpha^2 I \\ I_{c,ini} = \frac{\triangle V_c}{Z_1} = \frac{\alpha \triangle V}{Z_1} = \alpha\, I \end{cases} \tag{10}$$

Where, the subscript '*ini*' indicate the initial value. Using (9), the expression of I_E in (7) is written as:

$$I_E = -\left(\frac{1}{1+2K_0}\right)\frac{\triangle V}{Z_1} = -\ \frac{1}{1+2\,K_0}\ I \tag{11}$$

In (11) the relationship between earth current I_E and K_0 is inversely proportional. Therefore as K0 increases, the earth current IE during SPT condition decreases. At the same time, healthy phase's currents in (6) expressed as:

$$\begin{cases} I_b = K_b, K_b = \frac{(1+K_0)\,\alpha^2 - K_0 \alpha}{1+2\,K_0} \\ I_c = K_c\, I\,, K_c = \frac{(1+K_0)\alpha - K_0 \alpha^2}{1+2\,K_0} \end{cases} \tag{12}$$

Fig. 3 of [13] indicates the variation in ratios of *Ib / Ib,ini* and *Ic / Ic,ini* both in magnitude and phase angle versus the K_0. In the overhead transmission line, the value of K_0 is typically between 0.6 to 1 [3]. Fig. 3 of [13] represents as K_0 increases, the magnitudes of *Ib / Ib,ini* and *Ic / Ic,ini* decreases slowly. For K_0 value between 0.6 to 1, the magnitude of healthy phases current I_b and I_c during SPT are nearly 85% of their values prior to SPT.

The main result of the above analysis is that under the SPT condition, the earth current is present in the system. Therefore there is a need to block the operation of a protection system whose action is based on the earth current during the SPT condition.

II. Healthy Phases Currents during SPT

Consider Fig. 1(a), the impedance measured by phase b ground distance unit Z_{bE} is:

$$Z_{bE} = \frac{V_{bE}}{I_b + K_0 I_E} \tag{13}$$

Using the (11), (12), and assuming the voltage after and before the SPT is identical, the (13) can be written as:

$$Z_{bE} = \frac{\alpha^2 V}{\left(K_b - \frac{1}{1+2K_0}\right) I} = \frac{V}{I} \tag{14}$$

The impedance measured by ground distance unit Z_{bE} during the normal operating condition of a system is

$$Z_{bE,ini} = \frac{V_{bE,ini}}{I_{bE,ini}} = \frac{\alpha^2 V}{\alpha^2 I} = \frac{V}{I} \tag{15}$$

According to (14) and (15), the impedance measured by the ground distance unit under the steady-state condition of the system and during the SPT condition is identical. Moreover, the impedance measured by phase distance relays are given as follows:

$$Z_{ab} = \frac{\alpha^2 V}{K_b I}, Z_{bc} = \frac{(\alpha^2 - \alpha) V}{(K_b - K_c) I}, Z_{ca} = \frac{\alpha V}{K_c I} \tag{16}$$

The ratio of impedance measured by phase distance units, after the SPT and before the occurrence of SPT, is given as follows:

$$\frac{Z_{ab}}{Z_{ab,ini}} = \frac{\alpha^2}{K_b}, \frac{Z_{bc}}{Z_{bc,ini}} = 1, \frac{Z_{ca}}{Z_{ca,ini}} = \frac{\alpha}{K_c} \tag{17}$$

In Fig.4 of [13], for K_0 values between 0.6 to 1, the impedance measured by the phase distance units *ab* and *ca* during the SPT condition are higher than the impedance measured during the steady-state condition of a system by 1.15.

III. Asymmetrical Power Swing Impact on Distance Relay

The Performance of a distance relay under asymmetrical power swing is analyzed with the help of Fig. 1(a). For healthy phase *b* the following equation can be written by using the (1), (5), and (13).

$$V_{bx} = V_{by} + (Z_s - Z_m) I_b + Z_m I_E \tag{18}$$

$$I_b + K_0 I_E = \frac{V_{bx} - V_{by}}{Z_1} \tag{19}$$

$$Z_{bEx} = \frac{V_{bx}}{\frac{V_{bx} - V_{by}}{Z_1}} = Z_1 \frac{1}{1 - \frac{|V_{by}|}{|V_{bx}|} \angle -\delta(t)} \tag{20}$$

The (20) in Cartesian form is given as follows:

$$Z_{bEx} = \frac{Z_1}{1 - K_v(\cos\delta(t) + j\sin\delta(t))} \tag{21}$$

From (21), it is clear that for different values of *Kv*, the Variation of Z_{bEx} depends upon the power angle δ. From [13, Fig.7], it is observed that for some value of power angle δ, the impedance calculated by ground distance unit Z_{bEx} enters into the tripping zone of the relay. If the disturbance is severe, then the power angle separates by a large angle, and the impedance trajectory passes into opposite side of the RX plane represents that, the ensuing power swing is unstable.

The impedance measured by phase distance unit *bc* during the SPT of phase a is calculated by using (1) and (12).

$$V_{bx}\text{-}V_{cx} = (\alpha^2 - \alpha)V \text{ , } I_b\text{-}I_c = (\alpha^2 - \alpha)\frac{\Delta V}{Z_1} \tag{22}$$

$$Z_{bc} = \frac{V_{bx} - V_{cx}}{I_b - I_c} = Z_1 \frac{1}{1 - K_v \angle -\delta(t)} \tag{23}$$

Considering (16), the impedance calculated by phase distance unit *ab* and *ca* are given as:

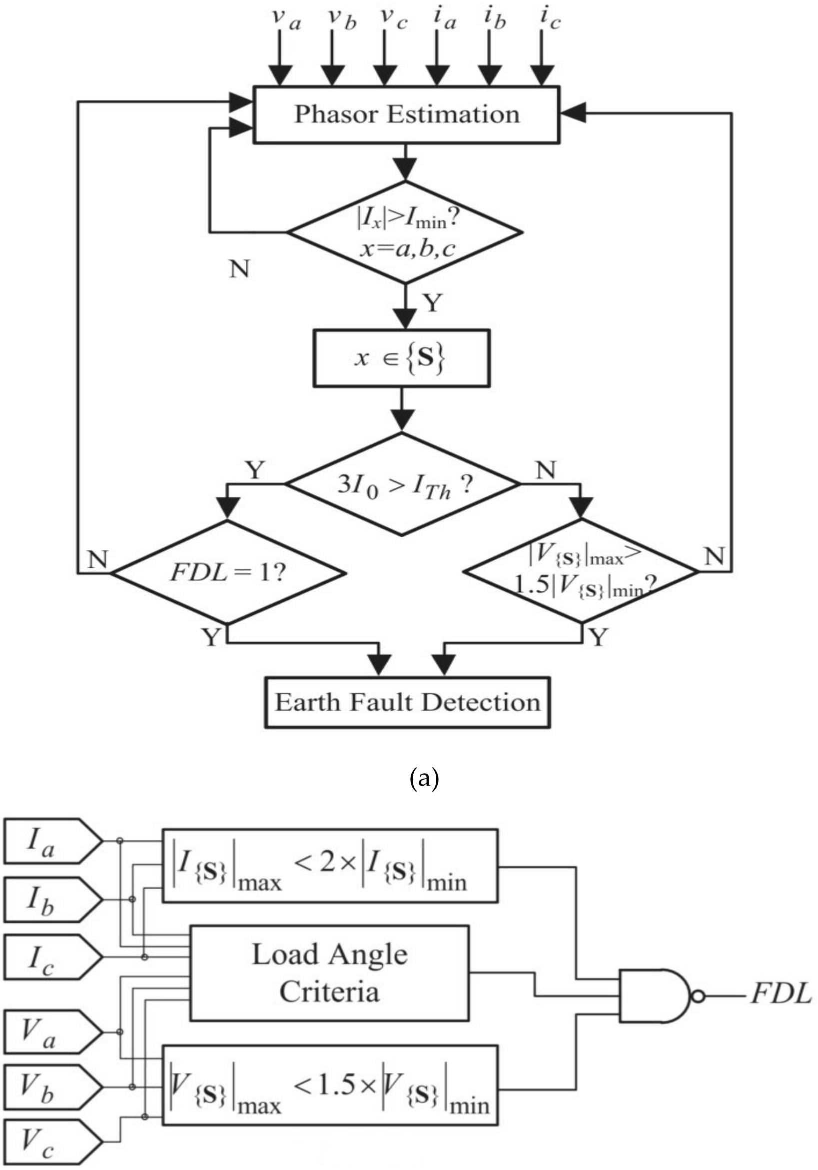
$$Z_{ab} = \frac{\alpha^2}{K_b} \cdot \frac{Z_1}{1 - K_v \angle -\delta(t)}, \quad Z_{ab} = \frac{\alpha}{K_c} \cdot \frac{Z_1}{1 - K_v \angle -\delta(t)} \tag{24}$$

It can be concluded from (16), (24) and [13, Fig. 4], that under the SPT condition, the impedance measured by the phase distance units *ab* and *ca* are higher than the impedance measured during the normal operating condition of a system. Therefore, the impact of asymmetrical power swing on the phase distance unit is less. However, the impedance measured by phase distance unit *bc* is identical to the impedance measured by ground distance units *bE* and *cE.*

IV. Proposed Earth Fault Detection Algorithm

Some recent numerical based distance relays incorporate an advanced earth fault detection algorithm under the SPT condition to restrain the undesired operation of ground distance relays. Such algorithm is defined in [14], suitable only under SPT conditions, and it does not consider the consequence of earth current on the adjacent line distance relays. Therefore to solve these issues, the earth fault detection algorithm is defined in Fig. 2. In the given algorithm, *Im* is the minimum value

Of the current used to identify any phase opened during the SPT. It is set as 10% of phase current (In) under normal operating conditions of the system. The load angle criteria block in Fig. 2 (b) monitor the angle ∣∠ V{s}/ I{s}∣ is above or below the load angle, 300.



(a)

(b)

Figure 2: *Algorithm to restrain the operation of ground distance relay under power swing: (a) Flowchart (b) Fault detection logic signal generation block.*

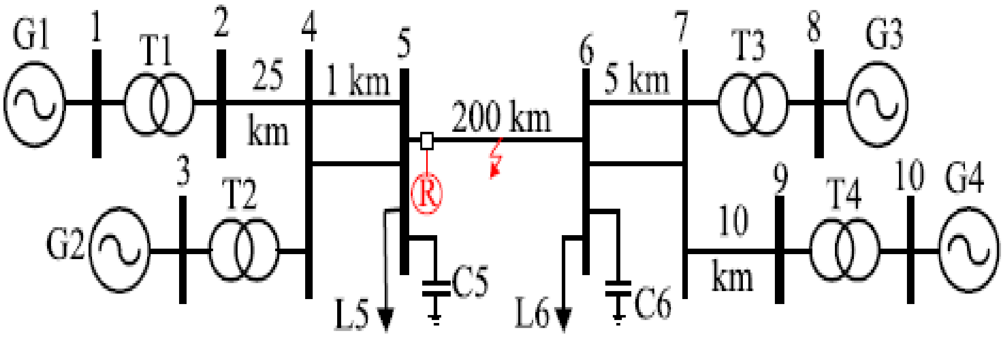


Figure 3: *Modified kundur four-machine 10 bus system*

V. Simulation and Result

To show the presented analysis two test systems are used in this section. Both the test systems are simulated in MATLAB software. The proposed algorithm is developed in Python language and tested on IEEE 9 bus system.

I. Modified Kundur four-machine 10 bus System

The modified kundur four-machine 10 bus system shown in Fig. 3 is used to show the impact of reclosing dead time on the performance of ground distance units. The relay under observation is connected at bus 5. The simulation parameters and it's data are given in [15]. The simulation scenario is discussed below:

Case 1: Consider an SLG fault at the midway of a line 5-6 at t = 2sec on phase a. To avoid the separation of two areas of the system, SPT needs to be performed under this situation. The SPT of phase a is performed at t = 2.06 sec, and finally, single-pole is reclosed at t = 2.3 sec due to the transient nature of the fault. Under this condition, the zero-sequence current is observed in line 5-6, which causes the unwanted operation of healthy phase ground distance units. Fig. 4 show the zero sequence current of line 5-6 during the SPT condition.

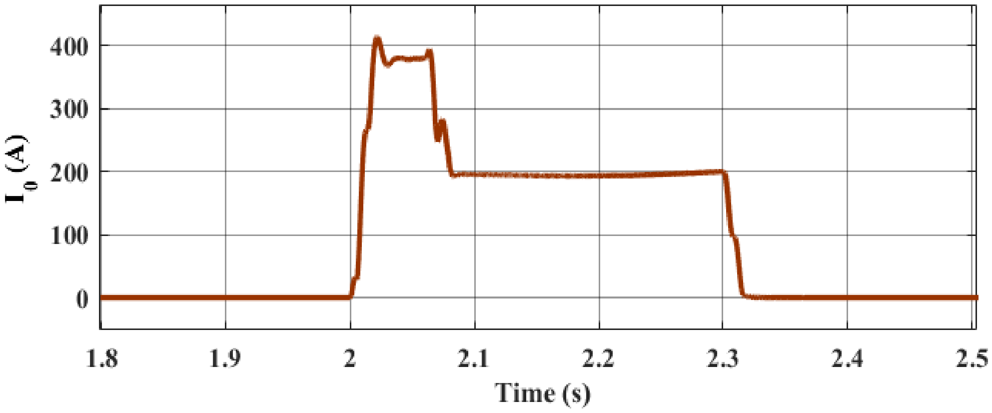
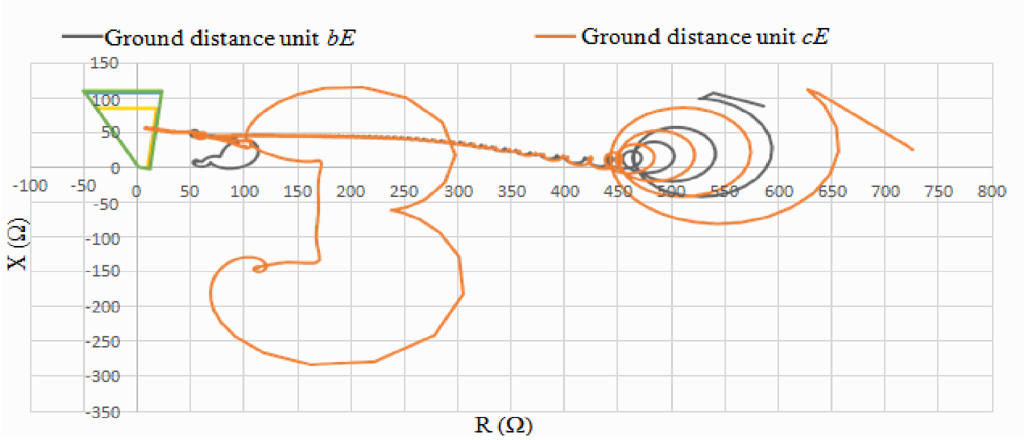
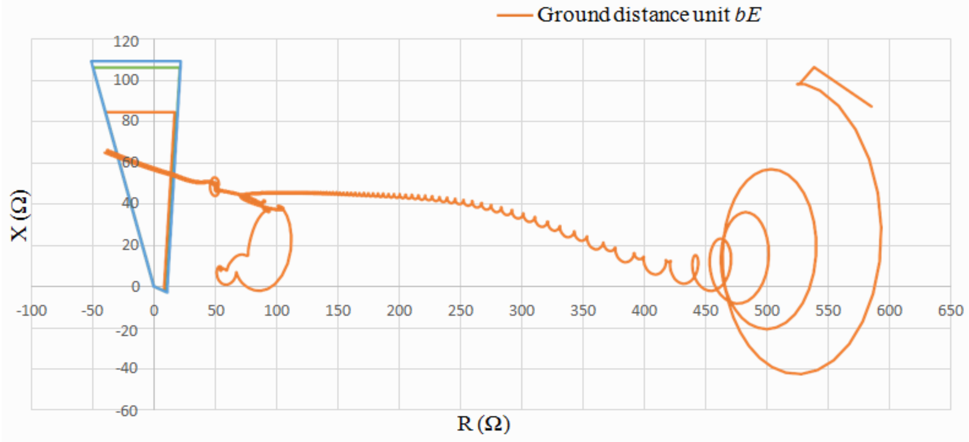


Figure 4: *Zero-sequence current of line 5-6 during SPT*

Case 2: Consider the SLG fault at the midway of line 5-6 at t = 3sec on phase a. The faulted phase a, is opened at t = 3.06 sec, and ultimately for defined dead time, the opened phase is reclosed. Fig. 5 show the behavior of the ground distance unit for two distinct reclosing dead times. The dead time is 35 cycles in Fig. 5(a) and 37 cycles in Fig. 5(b). For both this dead time, the impedance calculated by ground distance units enters into its tripping zone. Fig. 5 demonstrates that the ensuing power swing is stable for shorter dead time and unstable for the longer dead time.



(a)



(b)

Figure 5: *Behavior of ground distance relay under SPT of phase a of line 5-6: dead time = (a) 35 cycles, (b) 37 cycle.*

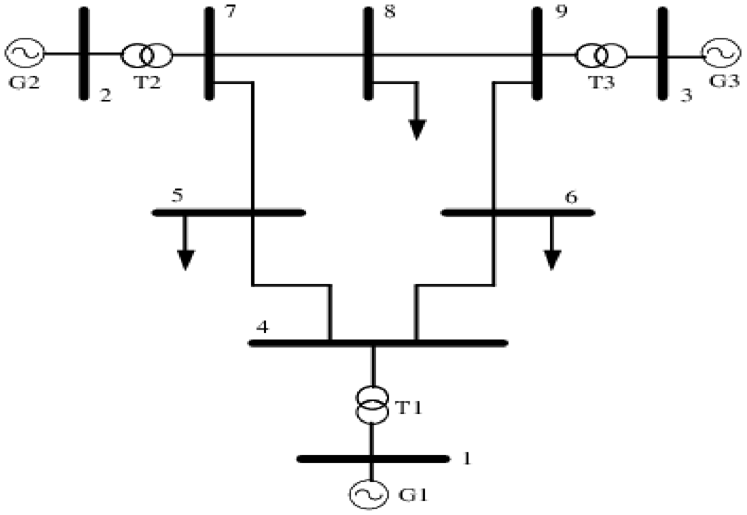


Figure 6: *IEEE 9-bus system*

II. IEEE 9 Bus System

The IEEE 9 bus system shown in Fig. 6, used to understand the impact of asymmetrical power swing on the adjacent line distance relays. It consists of three transformer, three generators, six transmission lines, and three loads. The data for all these parameters are given in [16]. The simulation scenario is as follows:

Consider the SLG fault at the midpoint of the line 6-9 at t = 1sec on phase a. The SPT of faulted phase is performed at t = 1.02 sec, and finally, the single-pole is reclosed at t = 1.3 sec. Under this situation, the considerable magnitude of zero sequence current is observed in adjacent line 4-6, which causes the unwanted operation of the ground distance units at bus 4. The zero sequence current in line 4-6 during SPT of line 6-9 shown in Fig. 7. The unwanted operation of ground distance units at bus 4 is restrained by using the algorithm defined in Fig. 2. In earth fault detection algorithm, max (∣ Ia ∣, ∣ Ib ∣, ∣ Ic ∣) is greater than 2×min (∣ Ia ∣, ∣ Ib ∣, ∣ Ic ∣) during SPT. However, under these same situations, the max (∣ Va ∣, ∣ Vb ∣, ∣ Vc ∣) is less than 1.5× min (∣ Va ∣, ∣ Vb ∣, ∣ Vc ∣). When SLG fault occurs at the midway of adjacent line 4-6 at t = 1.1 sec during the SPT of line 6-9, max (∣ Va ∣, ∣ Vb ∣, ∣ Vc ∣) becomes greater than 1.5× min (∣ Va ∣, ∣ Vb ∣, ∣ Vc ∣). Therefore, it is possible to restrain the operation of main line and its adjacent line distance relays during SPT condition by using the combination of voltages and currents which are defined in Fig. 2. The three phase voltages and currents shown in Fig. 8 are used during the testing of an algorithm.

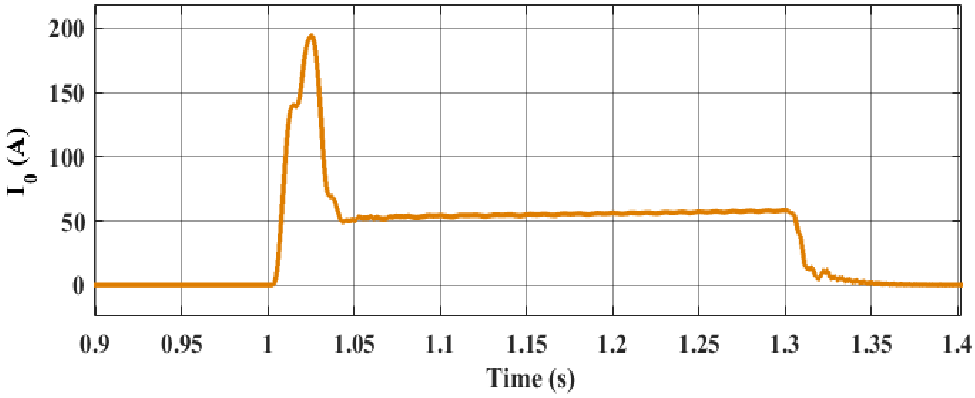
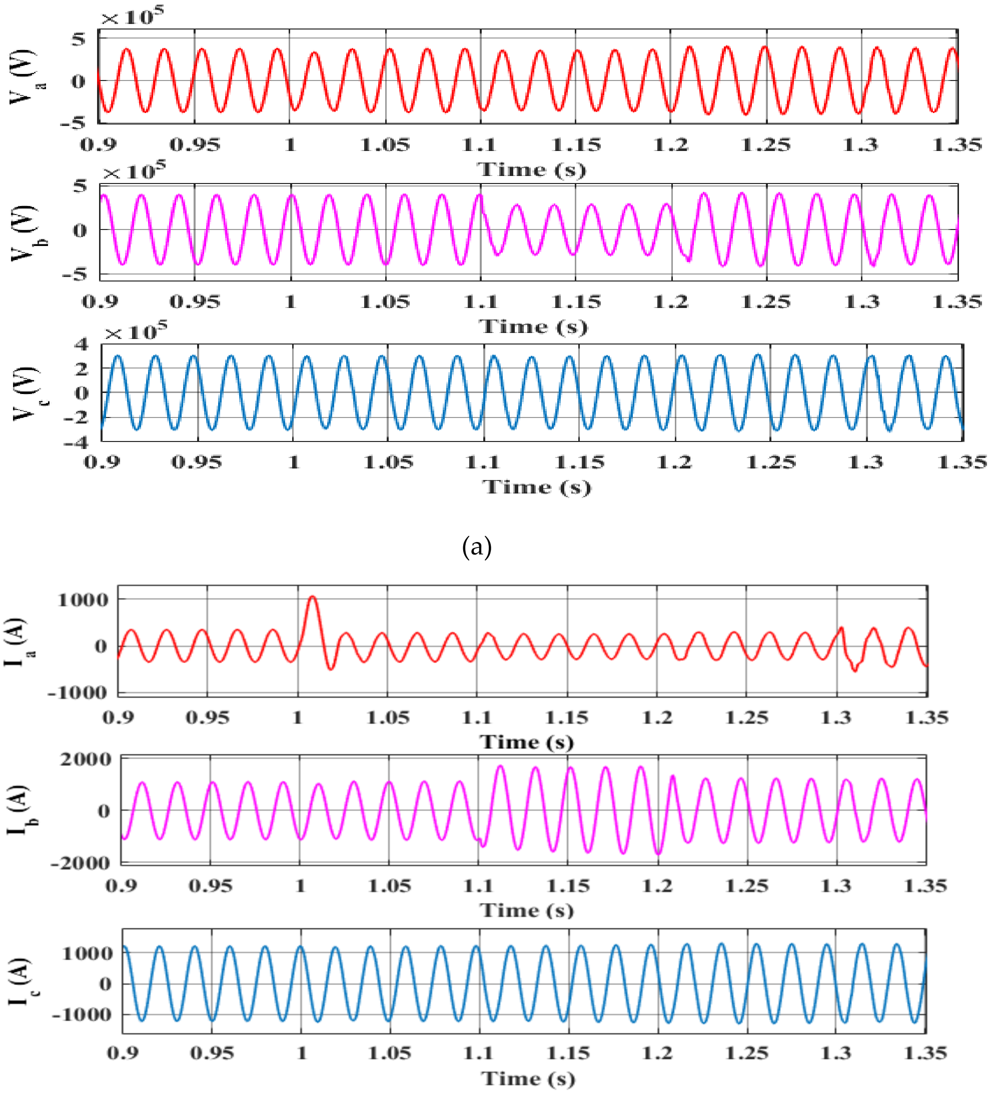


Figure 7: *Zero sequence current of line 4-6 during SPT of line 6-9*



(a)

(b)

Figure 8: *Simulation result of IEEE 9 bus system: (a) Three-phase voltage of line 4-6; (b) Three-phase current of line 4-6.*

VI. Conclusion

The distance relay performance under SPT condition and effect of asymmetrical power swing on distance relay are studied in this paper. The earth current is present in the system under the SPT condition, which causes the unwanted tripping of healthy phase ground distance units. This problem is solved in this paper by using the combination of voltages and currents which are defined in the earth fault detection algorithm. The earth fault detection algorithm takes care of undesired tripping of both the adjacent line and main faulted line distance relays, and it can be used in any situation regardless of SPT.

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