The Journal of CPRI,
Vol. 7, No. 2, September 2011 pp. 161–170

Application of Directional relay in an Ungrounded Power System to Locate Single Line to Ground Fault

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To locate the ground fault in an ungrounded power system is very difficult and challenging problem. The single phase to ground fault currents in these systems are much smaller than the required magnitude of ground fault detection devices to operate. It is also important to isolate the single phase to ground fault before restriking of second ground fault on the system to prevent a possible double phase to ground fault. Ungrounded power systems have an advantage of continue the operation with single phase to ground fault but it is also desirable and important to locate and isolate faulted feeder of the system. This paper addresses the potential of identifying faulted feeder by using a high sensitive directional relay which determines the fault current direction in the ungrounded power systems. A Matlab Simulink Model is developed for ungrounded 11 kV three feeder power system. Single phase to ground fault is created in each feeder and it is detected by directional relay.

1.0 INTRODUCTION

Single phase to ground fault detection in a power system is mostly dependent on the connection of the neutral. An ungrounded system can be defined as a system having no intentional ground connection between the system conductors and ground, except through potential measuring devices. However, in reality, the ungrounded system is actually capacitively grounded by the natural capacitance of energized components of the distribution system [1]. So for a single phase to ground fault in the system, the only path for ground current to flow is through the ground capacitance of the remaining system and the two unfaulted phases of the circuit. These fault currents are very small and does not have sufficient magnitude to be sensed by the conventional earth fault relays. This small fault current in the system does not require immediate clearing and provides an advantage to continue operating the system in spite of single phase to ground fault condition. Additionally, power quality is improved with the elimination of momentary voltage sags caused by single phase to ground faults in ungrounded system. Due to this advantage many countries Finland, England, China, etc has adopted this method where fault current is very small. Most of critical power systems like Navy shipboards, Medical systems, Process industries use ungrounded power systems, where system continuity is prime important.

An ungrounded power system provides these benefits, but is prone to transient overvoltage problems. During a single phase to ground fault, the line to ground voltages of the other two healthy phase increases to the line to line voltage result into stress on the insulation of the system equipments. This high-voltage can initiate a second fault at the weakest insulation point in the system. The second phase to ground fault initiates high fault current and can cause extensive damage to the system. Therefore identifying not only the first fault but the faulted section of the system is of prime importance for any ungrounded power systems.

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Ground fault in an ungrounded system can be identified by using the phase voltage measurement as voltage shifts uniformly throughout the system. Due to the small fault current, the detection of fault location in the system is difficult. The conventional method for fault isolation in an ungrounded system is switching method, in which the system operator de-energizes one feeder at time and continues until the fault disappears [2]. This process of finding faulty section disturbs the continuity of the system service, which is the advantage of ungrounded systems. The other method of fault detection is based on signal injection. A pulsating electronic signal injector is attached to the faulted network and operators with detectors trace the signal throughout the system for fault location. The injected signal travels along the fault path, and is detected by the receiver. This type of method is manpower intensive and requires well trained personnel who are familiar with the entire power system.

Some modern approaches utilize traveling-wave techniques for fault locating in ungrounded power systems. Techniques such as artificial neural networks [3] and wavelength transformation [4] have been used in order to extract the information about the fault location from the fault generated travelling wave. However, these methods have limited sensitivity, because the fault generated travelling waves in current and voltage signals are severely damped for high resistance fault.

Modern numerical relays have very improved and sensitive network protection which can estimate voltage and current phasor in fault direction. The success of these recently developed techniques provides helpful tools for solving difficult fault finding problems like for ungrounded power system. Many faults which can not be detected with electromagnetic relays can be captured by modern numerical relays which are more selective and sensitive.

L.Q1 [5] *et al*. proposed a new generalized method to solve the modeling incompatibility problems in ungrounded stiffly connected power systems. Joseph [6] *et al*. presents the effects of capacitance on high resistance grounded mine distribution systems. Louis [7] *et al*. presented an approach to simultaneous ground fault isolation for ungrounded power systems by using concepts on current differential and directional over current design. Yanzhe Li [8] *et al*. provide an analysis of the practical criterion for single phase to ground fault in ungrounded power system. Jin Wangyi [9] *et al.* presented a method of measuring capacitive current for ungrounded distribution systems. Ronald [10] *et al*. reviewed applications and future trend of impedance grounded systems and summarized available directional elements for ground fault detection in impedance grounded systems. John [11] *et al*. has given directional over current concepts. Ke Zhu [12] *et al*. presented a method for identification of faulted line using controlled short circuit of PT delta-connected windings. Soon-Ryul [13] *et al*. proposed a single phase to ground fault location algorithm for ungrounded radial distribution system using voltage and implementing ZCT in the system. Baldwin [14] *et al*. proposed method to use directional ground fault indicator to locate the fault in high resistance grounded systems.

The fault section in an ungrounded system can be detected by knowing the direction of the fault current. A fault current always flows from source to the fault location. The angular difference between the fault current and the reference voltage phasor determines the direction of the fault. This paper explains the application of directional relay to locate single phase to ground fault in an ungrounded power system. The directional relay responds to the direction of the fault current, since fault current can flow in direction, forward or reverse, depending upon the location of the fault. Zero sequence current is used for the operation of the directional relay. The protection method relies on directional protection by making use of the zero sequence quantities of the currents. The zero sequence current for single phase to ground fault mostly depends on the phase to ground capacitance of the system. Simulation test done in Matlab/Simulink software for the fault detection & results on the performance of directional protection are presented.

2.0 SINGLE PHASE TO GROUND FAULT CHARACTERISTICS

Single phase to ground fault current in an ungrounded system is quite small as there is no intentional neutral groundings in ungrounded system. In these systems, the currents of single phase to ground faults depend mostly on the phase to ground capacitance of the system. The system is connected to ground through parasitic capacitance, i.e. the line to ground capacitance (C_{RG}, C_{YG} and C_{BG}). The loads are connected ungrounded phase to phase and therefore, the distributed capacitance to ground forms the unintentional ground to the system. Figure.1 shows phase to phase load and phase to ground distributed capacitance that primarily determine ground current magnitude. The large capacitive impedance of ungrounded systems limits ground fault current and has virtually no effect on the phase to neutral voltage of the faulted phase.

When a single line to ground fault occurs, the faulted phase voltage, decreases to near zero and the healthy phase increases by a factor of √3. At the same time, the zero-sequence voltage increases to three times the normal phase to ground voltage. The uncollapsed voltage triangle during a ground fault means that the system can operate normally in the presence of a single line to ground fault. Figure 2 shows an unfaulted ungrounded power system and Figure 2 shows how the voltage triangle shifts relative to ground for a single phase to ground fault.

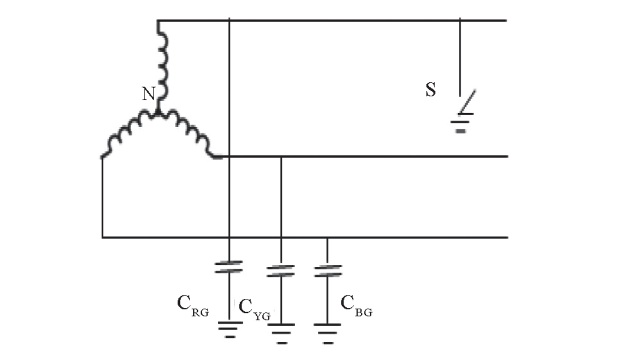

FIG. 1 UNGROUNDED POWER SYSTEM

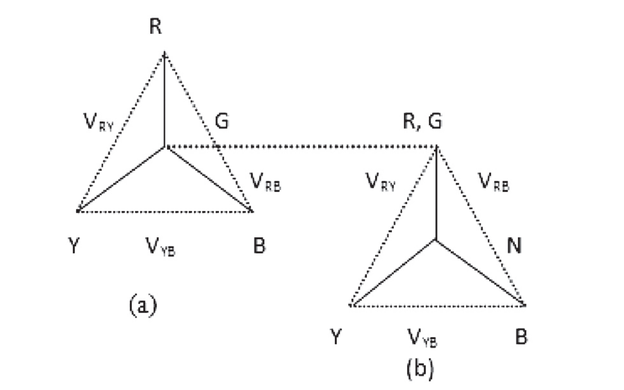

FIG. 2 VOLTAGE TRIANGLE (A) UNFAULTED SYSTEM. (B) FAULTED SYSTEM (R PHASE TO GROUND FAULT)

The ground faults in a system can be detected through the use of voltage transformers connected in wye-open delta configuration as shown in Figure 3. This method provides information that single phase to ground fault has occurred in the system but it does not give any information about the exact location of single line to ground fault.

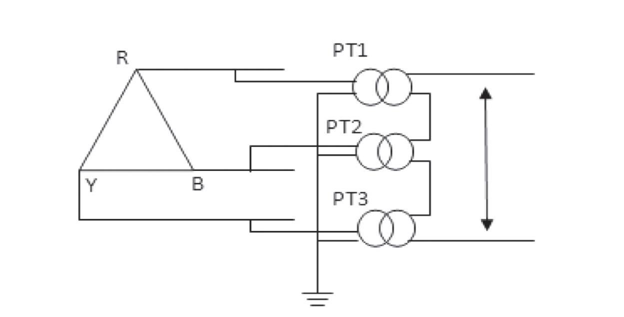

FIG. 3 OPEN DELTA CONFIGURATION TO DETECT GROUND FAULT

If a ground fault occurs on one phase, the voltage will reflect in the secondary side of open delta configuration. A resistor is connected across the transformer secondary to minimize the possibility of ferroresonance.

Single line to ground faults is approximately 80 % of all faults on a grounded power system, while the power interruption because of ground faults in ungrounded system is very less. This characteristic of ungrounded system makes this system popular in industries. On the other hand, limited ground fault current can cause difficulties with ground fault protection in these systems. Fault current can flow in either direction, forward or reverse. The fault zone can be detected by identifying the direction of the fault current and this can be done by implementing directional relay.

3.0 THE SYSTEM BEHAVIOUR DURING SINGLE TO GROUND FAULT

Considering 'R' phase to ground fault in the system shown in Figure 4. The three phase voltage vector and three line voltage vectors remain symmetrical, so load on the system does not get affected. However, the three phases to ground voltages have been changed. For the faulted phase 'R', the phase to ground voltage '$V^{(1)}_{RG}$' becomes zero and for unfaulted phases '$V^{(1)}_{YG}$' and '$V^{(1)}_{BG}$' it increases by √3 times and becomes equal to system line voltage.

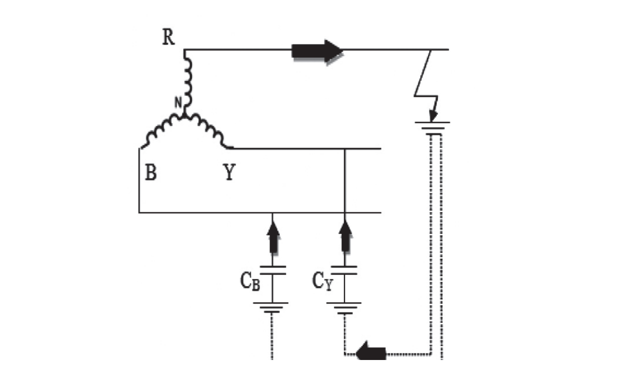

FIG. 4 R-PHASE TO GROUND FAULT

As the phase to ground voltage of the system has changed, the phase capacitive current also changes accordingly. There will be no capacitive current in R-phase as it was shorted with ground. Y-phase capacitive current $I^{(1)}_{CY}$ and B-phase capacitive current $I^{(1)}_{CB}$ increases by √3 times. The capacitive currents $I^{(1)}_{CY}$ and $I^{(1)}_{CB}$ lead respective phase to ground voltage by 90°. The capacitive currents form loop by the fault point of the faulted phase. Thus the fault current $I^{(1)}_{f}$ can be represented as the vector sum of healthy phases charging currents $I^{(1)}_{CY}$ and $I^{(1)}_{CB}$ but the direction will be reverse to the charging currents.

4.0 DIRECTIONAL PROTECTION FOR AN UNGROUNDED POWER SYSTEM

When an ungrounded power system is used to supply two or more loads by two or more cables in parallel, the protection on these feeders would operate simultaneously for a fault occurring one of them. To obtain selective protection directional relays can be used. The directional relay checks the direction of the residual current and allows the unit to operate if the current is in the reverse direction. The setting of these relays should be approximately 1.5 times the capacitive current of the protected feeder. This is due to the fact that when a fault occurs on a nearby feeder, the capacitive current returns up to the healthy feeder and flows into the fault, thus causing a risk of tripping the healthy feeder if the relay setting is too low.

The directional relay compares the torque (T) calculated from the residual current against the preset torque value. When T is positive and above the threshold value, the relay declare it as a forward ground fault and when T is negative and below threshold value the relay declare it as a reverse ground fault.

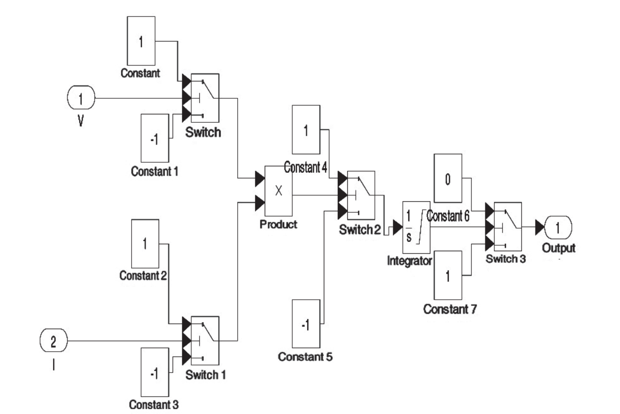

FIG. 5 SIMULINK MODEL FOR DIRECTIONAL RELAY

5.0 FAULTED FEEDER DETECTION IN AN UNGROUNDED POWER SYSTEM

The zero sequence impedance of an ungrounded system has a very high magnitude. This high value permits us to ignore the positive and negative sequence impedances without significant loss of accuracy when evaluating single line to ground faults. Figure 6 shows an approximate zero sequence representation of the forward ground fault in the system depicted in Figure 1.

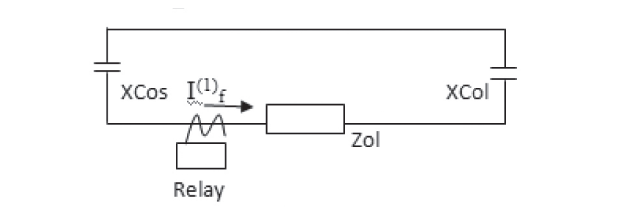

FIG. 6 ZERO-SEQUENCE NETWORK FOR FORWARD GROUND FAULT

In Figure 6 the relay measures current through XCos, where XCos is the zero sequence impedance of the remaining part of the system.

In Figure 7 the relay measures current through the series combination of (Zol + XCol), where Zol is the zero sequence line impedance and XCol is the line to ground capacitance of the protected line. Thus, the relay measures –XCos, for forward faults and (Zol + XCol) for the reverse faults. The directional relay, compare zero sequence impedance against forward fault and reverse fault thresholds to determine the direction of the ground fault.

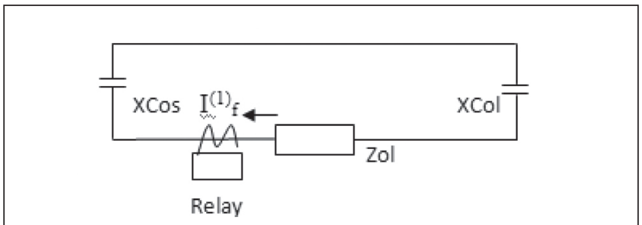

FIG. 7 ZERO-SEQUENCE NETWORK FOR REVERSE GROUND FAULT

Figure 8 represents an ungrounded distribution system with a solid R-phase to ground fault in feeder-3. We can observe that the fault current $I^{(1)}_f$ depends on line to ground capacitance of the unfaulted phases. The voltage measurement instrument used in this system is open delta transformer which supplies all protective feeders on the bus system with residual voltage to determine the direction of a ground fault.

The current measurement for directional relay is carried out by core balanced current transformer or a toroidal current transformer. Figure 2 shows the voltage phasor diagram for the power system with R-phase to ground fault. Figure 9 represents the phasor diagram of the fault current flowing through the faulted and unfaulted feeders of the system given in figure 8.

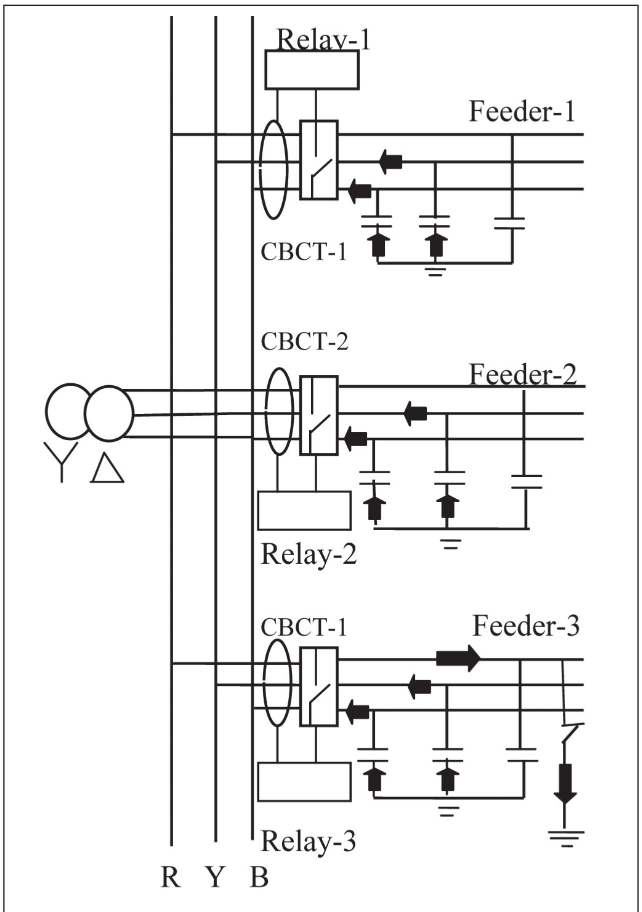

FIG. 8 R-PHASE TO GROUND FAULT AT FEEDER-3 OF AN UNGROUNDED POWER SYSTEM

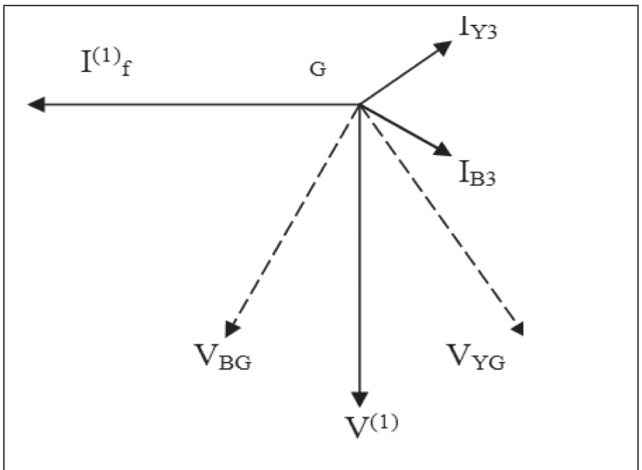

FIG. 9 PHASOR OF RESIDUAL VOLTAGE and RESIDUAL CURRENT FLOWING THROUGH THE FAULTED FEEDER

From Figure 9 it can be seen that the fault current $I^{(1)}_f$ lags the residual voltage $V^{(1)}$ by 90°. For comparing the direction of fault current, phasor diagram of residual voltage and residual current is given in Figure 10.

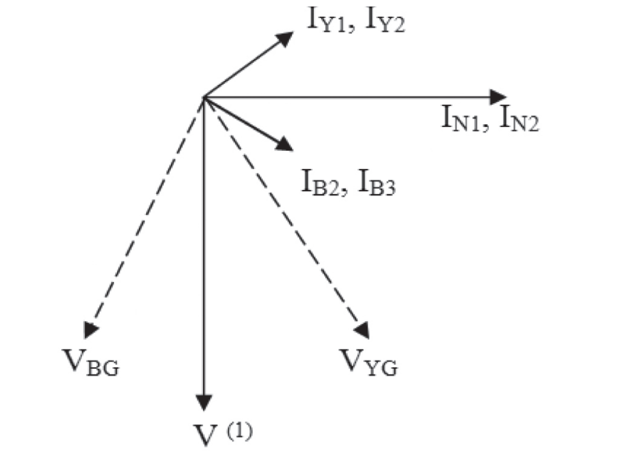

FIG. 10 PHASOR OF RESIDUAL VOLTAGE AND RESIDUAL CURRENT FLOWING THROUGH THE UNFAULTED FEEDERS

It can be seen from figure 9 and figure 10 that for the faulted feeder case, the residual current or the fault current lags the residual voltage $V^{(1)}$ by 90° and in unfaulted feeders, the residual currents lead the residual voltage $V^{(1)}$ by 90°. From this observation, it can be concluded that the fault is in front of the relay if the residual current lags the residual voltage by 90° and the fault is behind the relay if the residual current leads the residual voltage by 90°. So by simply comparing residual voltage to residual current, faulted feeder can be identified.

6.0 MODELING OF AN UNGROUNDED POWER SYSTEM IN MATLAB/ SIMULINK

As described in above section, the proposed fault detection method is based on the analysis of the phasor relationship between zero sequence voltage and current at each feeder. The analyzed model as shown in Figure 11 is a simplified ungrounded 11 kV system. The 11 kV network is fed from the 110/11 kV transformer. The ungrounded system has three outgoing feeders, which feed to the loads through distribution cables and distribution transformers. Directional relays are placed at each feeder for sensing fault current directions. The fault current produced is because of distributed capacitance of the cables. The details of the ungrounded system configuration are given in Table 1.

The charging current or the residual current is measured by the vector sum of the three phase currents in each feeder. The directional relays are fed by this residual current, which identifies the direction (forward or reverse) and gives digital output. The output is zero if the direction is reverse and the output is one if the residual current is in forward direction. That means for the faulted feeder the output of directional relay is zero and for the unfaulted feeders the output will be one. The output of the relay can be used in the system for alarm or tripping of faulty section according to the requirement of the system.

Preferably alarm can be used to indicate the faulty section in the system. So the system operator can decide whether to isolate or to keep in operation. In unfaulted condition, output of the relay remains one in all feeders as shown in Figure 12.

The out put of all relays are '1' which indicates that the system is healthy and there is no single line to ground fault in the system (Figure 13). During healthy condition the magnitude of open delta voltage also remains very low. The charging currents magnitude also remains low.

A single phase to ground fault is created in feeder-3 by closing the breaker in feeder-3. The directional relay output in healthy feeder remains '1' where as in faulty feeder it becomes '0', which indicates that there is a ground fault in feeder-3 of the system. The voltage of open delta transformer also found to be increased as shown in Figure 14.

It can be seen that the direction of charging current becomes reverse as compared to the unfaulted feeders. The output characteristics of each feeder in single phase to ground fault in feeder-3 are given in Figure 15.

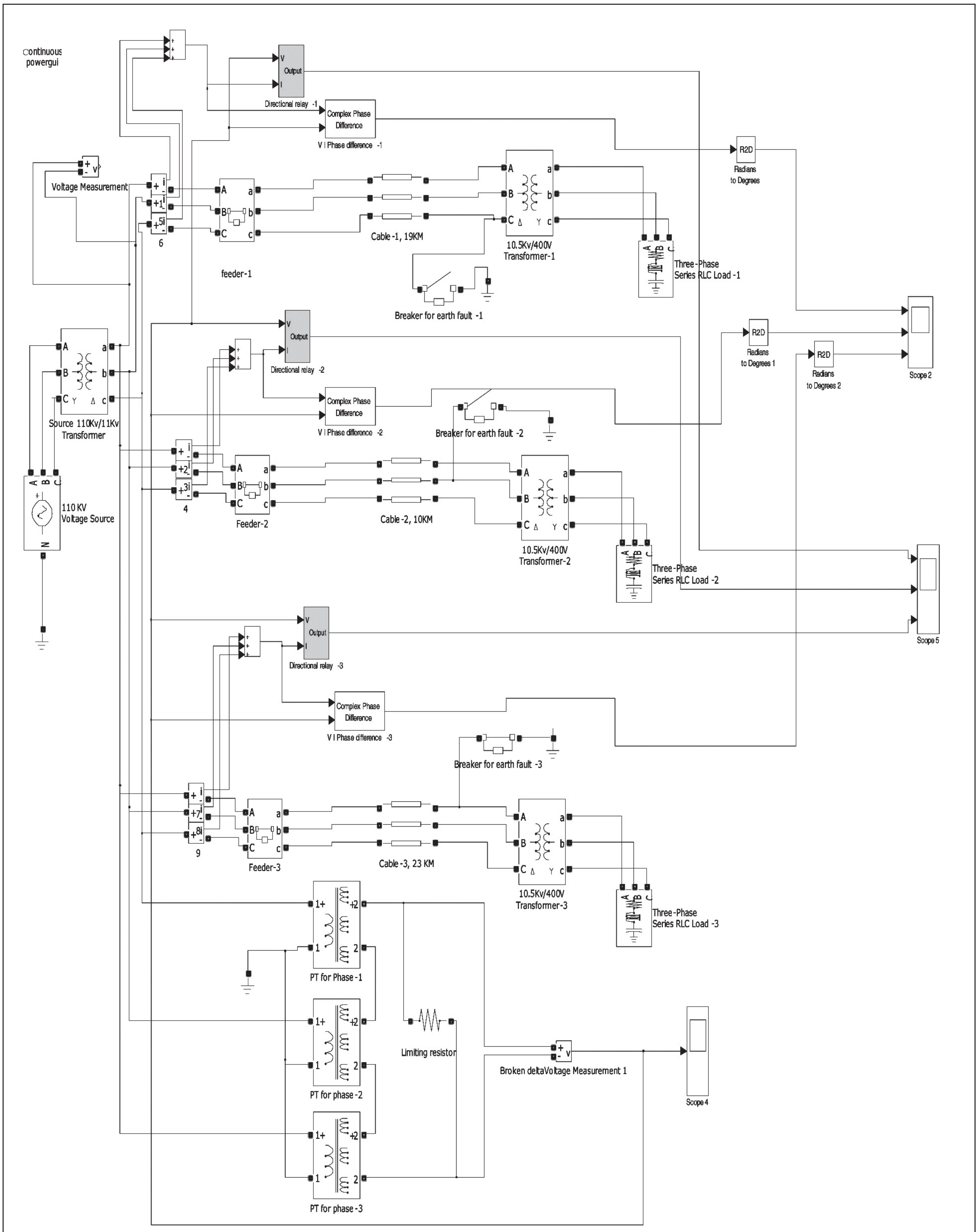

FIG. 11 UNGROUNDED POWER SYSTEM MODEL WITH `R` PHASE TO GROUND FAULT IN FEEDER-3

TABLE 1

NETWORK PARAMETERS OF THE SYSTEM

Source voltage		V_{source}		**110 kV**
Source transformer		Configuration		Y/d11 40 MVA 110 kV/ 11 kV
Cable		R_1, R_0 (Ohms/km)		1.097,0.079
		L_1, L_0 (H/km)		$3.5014e^{-4}$, $2.4192e^{-4}$
		C_1, C_0 (F/km)		$0.28e^{-6}$, $0.51e^{-6}$
		Length	Feeder-1	19 km
			Feeder-2	10 km
			Feeder-3	23 km
Load transformers		Configuration		D11 / y, 10 MVA, 11 kV/ 400 V
Open delta Potential transformers		Configuration		11 kV / 110 V
LV Load details(W)	Feeder-1	Active power		$6.3e^{6}$
		Inductive reactive power		$1.5e^{6}$
		Capacitive reactive power		$0.15e^{6}$
	Feeder-2	Active power		$5.7e^{6}$
		Inductive reactive power		$1.3e^{6}$
		Capacitive reactive power		$0.14e^{6}$
	Feeder-3	Active power		$6.8e^{6}$
		Inductive reactive power		$1.7e^{6}$
		Capacitive reactive power		$0.19e^{6}$

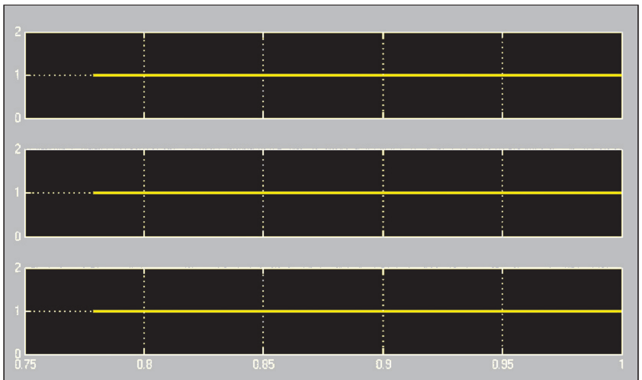

FIG. 12 OUTPUT OF DIRECTIONAL RELAYS AT FEEDER-1, FEEDER-2 AND FEEDER-3 IN HEALTHY CONDITION

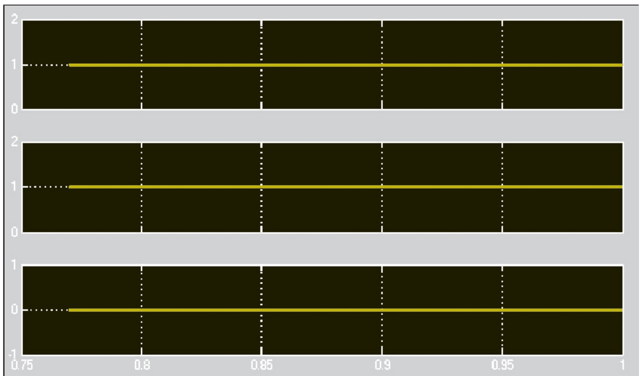

FIG. 13 OUTPUT OF DIRECTIONAL RELAYS AT FEEDER-1, FEEDER-2 AND FEEDER-3 DURING SINGLE LINE TO GROUND FAULT IN FEEDER-3

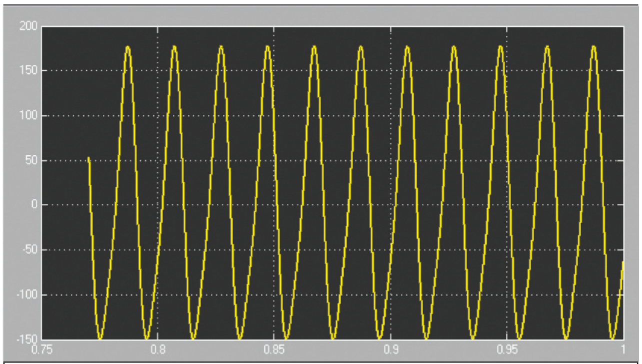

FIG. 14 VOLTAGE OUTPUT OF OPEN DELTA PT

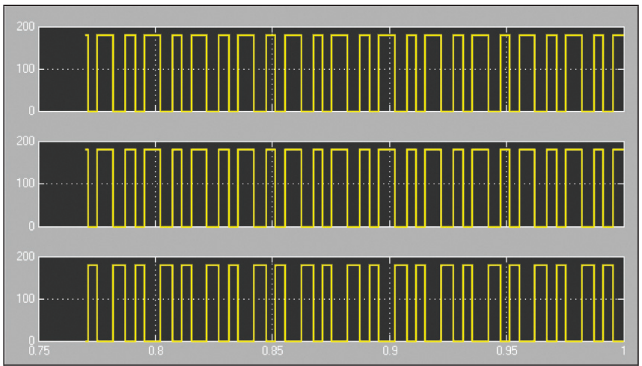

FIG. 15 RESIDUAL CURRENT AND RESIDUAL VOLTAGE PHASE DIFFERENCE IN RADIAN/SEC DURING SINGLE PHASE TO GROUND FAULT IN FEEDER-3

It can be shown from Figure 15, for feeder 1 and 2 the residual current direction is reverse and for feeder-3, it is in forward direction. The directional relay provided in each feeder senses the direction of fault current and provides output accordingly. For simulation three test cases are considered.

Case-1: Single line to ground fault at feeder-1 in phase-B.

Case-2: Single line to ground fault at feeder-2 in phase-Y.

Case-3: Single line to ground fault at feeder-3 in phase-R.

The output characteristics of directional relay are summarized in Table 2.

As shown in the output characteristics of the system, the results of the test cases are all found to be accurate. The directional relay output of faulted feeder is found to be 'zero' and other two healthy feeders it is 'one'. The phase differences between residual current and phase voltage also found to be same as proposed. For the faulted feeder, the direction of residual current is reverse and for healthy feeders it is found to be forward.

TABLE 2

SUMMARY OF OUTPUT CHARACTERISTICS

	Directional relay output			**Open Delta PT voltage**
	Feeder-1	Feeder-2	Feeder-3	(V)
Before fault	1	1	1	15
'B' phase fault in feeder-1	0	1	1	200
'Y' phase fault in feeder-2	1	0	1	234
'R' phase fault in feeder-3	1	1	0	192

7.0 CONCLUSION

A novel technique for identifying the faulted feeder in an ungrounded system is proposed. The direction of residual current in an ungrounded system is used as to identify the faulted feeder or the section of the system. Current polarized directional relays can provide desired results in the application of identifying single phase to ground fault in ungrounded systems.

A three feeder model is developed in Matlab/ Simulink which allows customized construction and connections of different components. The effectiveness of proposed technique and customized model is verified in different conditions and locations of ground fault. The evaluation results show that the proposed method performs well.

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