

Pilot Directional Protection Scheme Using Wireless Communication

Nitish Sharma, G. G. Karady

Abstract—This paper presents a scheme for the protection of loop system from all type of faults using the direction of fault current. The presence of distributed generation in today's system increases the complexity of fault detection as the power flow is bidirectional. Hence, protection scheme specific to this purpose needs to be developed. This paper shows a fast protection scheme using communication which can be fiber optic or wireless. In this paper, the possibility of wireless communication for protection is studied to exchange the information between the relays. The negative sequence and positive sequence directional elements are used to determine the direction of fault current. A PSCAD simulation is presented and validated using commercial SEL relays.

Keywords—Smart grid protection, pilot protection, power system simulation, wireless communication.

I. INTRODUCTION

THE FREEDM, or Future Renewable Electric Energy and Distribution Management [1] project is a collaborative research project currently under development by five universities. The goal of the research is to integrate conventional as well as non-conventional sources of power generation into the power grid. The pilot directional protection system is used to detect the existence and location of faults at very high speeds. A simplified communication scheme is presented which could be helpful in detecting the fault direction. The current sequence components are used to determine the fault location. A radial system using commercial SEL relays is presented to validate the method used for the protection. This scheme is designed to serve the main protection scheme of the FREEDM green hub smart distribution system. The pilot protection scheme configuration offers a considerable advantage when compared with fast fuses, which need replacement following a fault occurrence. In this paper a section of FREEDM loop is used for the study purposes, the goals of this study are to validate the system within this radial system. This is achieved by constructing an accurate model of the pilot protection system in PSCAD and building a hardware model to validate the simulation.

FREEDM system supports bi-directional flow of power. Therefore, conventional protection systems are inadequate to use as they are designed mainly for the radial distribution configurations with unidirectional power flow [2]. Also, fault clear time will ensure whether the system will lose stability or not. Moreover, loop systems have higher short circuit currents

and also increase the dips in voltage as well as frequency. Thus making these systems more sensitive to power system oscillations and fault expansion. A high-speed communication system is required for the protection system due to the increased penetration of renewable energy in the grid [3]. The use of power line communication between the relays was first introduced in [4]. The traditional distribution protection system can do identification and interruption time in more than a second. One of reasons for this could be that classical mechanical circuit breaker, are capable to turn off the fault current only at zero crossing current point, and hence the require at least a cycle to interrupt/cut off the circuit. Also, the distance relay operates by comparing the calculated apparent impedance to the reach point impedance of the relay. Protection coverage zones are defined for distance relays but they suffer from the problem of under reach and overreach. A new scheme based on the negative sequence components for the protection was first demonstrated in the paper, as in [5]. It requires the calculation of the negative sequence components to detect the fault direction but this scheme was highly dependent on the strength of the source. The effect of strength of source was overcome successfully in the paper, as in [6] and [7]. The use of negative sequence impedance for detecting the fault direction was successfully shown in the paper. The proposed protection scheme is tested on a loop system in PDCAD. Simulation results are presented and compared with a conventional protection scheme to show the effectiveness and robustness of the proposed approach.

The reminder of the paper is organized in five major sections. Pilot protection operating principles are presented in Section II. The design problem and the simulation results in PSCAD are presented in Sections III and IV. In Section V, hardware implementation is presented followed by any conclusions in Section VI.

II. PILOT PROTECTION SYSTEM PRINCIPLES OF OPERATION

A comprehensive scheme has to be developed for the FREEDM loop which could be used to detect all type of fault in the system. The protection scheme is divided into two schemes. The first scheme is used to detect the asymmetrical faults while the second scheme is used to detect the symmetrical faults.

A. Detection of Asymmetrical Faults

The negative sequence directional element is used to determine the direction of fault current. A negative sequence directional element calculates the negative sequence impedance to determine the fault location, as given in [8]. This

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calculated quantity is compared with two threshold values to determine whether the fault is in forward or reverse direction to a relay.

$$Z_2 = \frac{\text{Re}[V_2 \cdot (I_2 \angle \theta)^*]}{\text{Re}[(I_2 \angle \theta) \cdot (I_2 \angle \theta)^*]} = \frac{\text{Re}[V_2 \cdot (I_2 \angle \theta)^*]}{I_2^2} \quad (1)$$

V_2 = Negative sequence voltage,
 I_2 = Negative Sequence current,
 Z_2 = Negative Sequence Impedance

During the normal operation, negative sequence impedance lies within the forward threshold and reverse threshold values indicating no fault in the system. But during a fault, the sequential component comes into play and negative sequence impedance (Z_2) can be used to determine the fault location. If the calculated Z_2 is less than the forward threshold impedance, then the fault is in the forward direction to the relay. If the calculated Z_2 is greater than the reverse threshold impedance, then the fault is in the reverse direction to the relay. During a symmetrical fault, negative sequence components are negligible in the system and the directional element fails to detect the fault. To overcome this particular scenario, the relay uses positive sequence components during three phase faults to detect the directionality of the fault current. The previous value of voltage and current phase and magnitude is compared with the present value of voltage and current magnitude and phase in the circuit. Any inconsistency in the two values indicates the presence of the fault.

B. Symmetrical Faults

The positive sequence based directional element is used to detect the symmetrical fault in the circuit. During an asymmetrical fault in the system, the presence of negative sequence elements can be used to determine the directionality of fault current. But, in the case of symmetrical faults, the negative sequence elements are almost zero as the system remains balanced even after the fault. Hence, the negative sequence elements cannot be used for detecting the fault.

A new scheme is to be developed which along with negative sequence element can be used to determine the directionality of fault, as in [9]. When there is a fault in the system, the voltage and current magnitude and phase difference at that point changes. The present voltage and current waveforms are compared with the previous history of the corresponding waveforms a few cycles before. This change in voltage and current waveform is used to determine the directionality of fault in the system.

The normal positive sequence voltage and current at 60Hz frequency are taken as reference phasor to represent the healthy condition in the system. The same waveform is delayed by few cycles after the occurrence of the disturbance, to represent the healthy condition in the circuit prior to the fault. After the fault in the system, the normal waveforms will represent fault in the circuit and these will be compared with delayed waveforms to calculate the change in voltage, current magnitude and phase angle. The positive sequence element

calculates the change in voltage and current phase angle. This change is used to determine the fault direction.

$$\Delta V_1 = V_{1f} - V_{1\text{prefault}} \quad (2)$$

$$\Delta I_1 = I_{1f} - I_{1\text{prefault}}$$

$$\theta = \angle \Delta V_1 - \angle \Delta I_1$$

ΔV_1 = change in positive sequence voltage after and before the fault;
 ΔI_1 = change in positive sequence current after and before the fault

$\theta > 0$: Reverse fault

$\theta < 0$: Forward fault

III. IMPLEMENTATION OF PILOT PROTECTION SCHEME IN PSCAD

A. Detection of Asymmetrical Faults

The sequence components of currents and voltages are obtained from the fundamental phase quantities and are given as inputs to the negative sequence directional element 32Q available in PSCAD. The negative sequence directional element stays idle during the normal operation but generates +1 or -1 depending on the fault location. The negative sequence impedance is used as a deciding factor to determine the fault location.

For a phase to ground fault, the voltage of un-faulted phases of the relay is used to detect the imbalance. Similarly, for a line-line fault, it uses the voltage of the un-faulted phases. But for a three-phase-to-ground fault, the sequence components are less dominant, and therefore, it fails to detect the direction of fault. This hurdle is overcome when digital relays are used. Digital relays (SEL 351S) invoke their internally stored memory voltage during a three phase to ground fault. Fig. 1 shows the implementation of the directional element (32Q element) in PSCAD.

Fig. 1 shows the method to obtain sequence components required for the operation of negative sequence directional element. If the calculated Z_2 is less than forward threshold impedance Z_{2F} , the directional element generates +1 and if the calculated impedance is greater than the reverse threshold impedance Z_{2R} , it generates an output of -1. During normal operation, the output remains zero.

B. Detection of Symmetrical Faults

The currents and voltages sequence components are obtained from the fundamental phase quantities. These positive sequence voltage and current signals are delayed by one cycle and being continuously compared with the present components of positive sequence voltage and current.

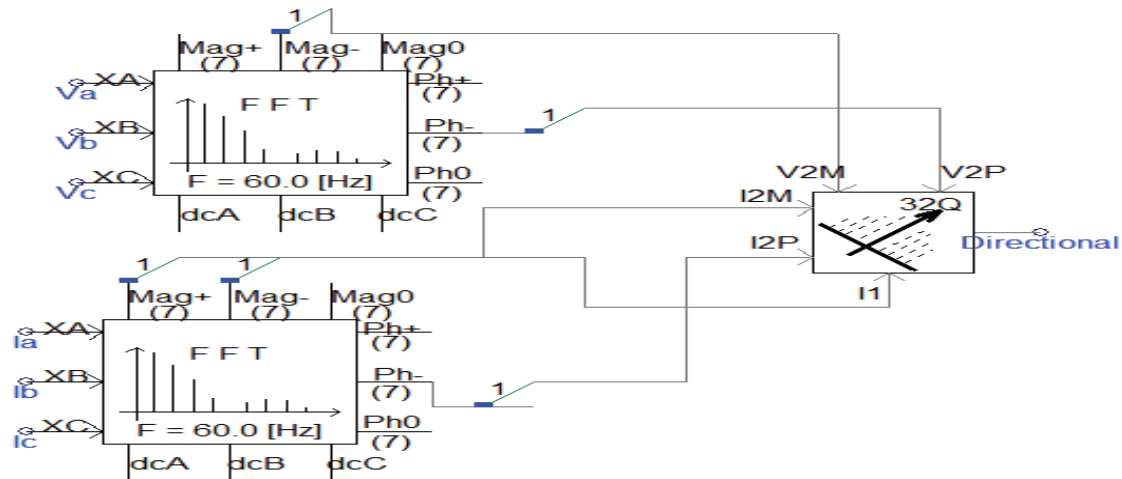


Fig. 1 Implementing Directional Element in PSCAD

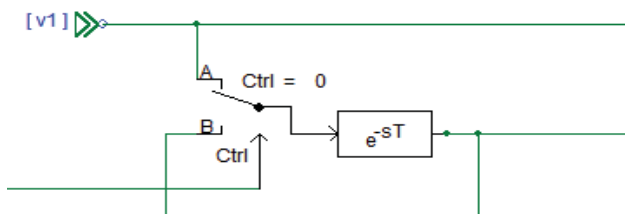


Fig. 2 Positive Sequence Signal and Delayed Signal in PSCAD

The measurement process commences only when the control signal goes high, as given in [9]. When there is no fault in the circuit, the change in voltage and current is zero but under the influence of fault, the change becomes non-zero. A control signal is based on the overcurrent element in the circuit. With a fault in the circuit, overcurrent element goes high. Hence, enabling the calculation of the difference in voltage and current phase angle as shown in Fig. 3.

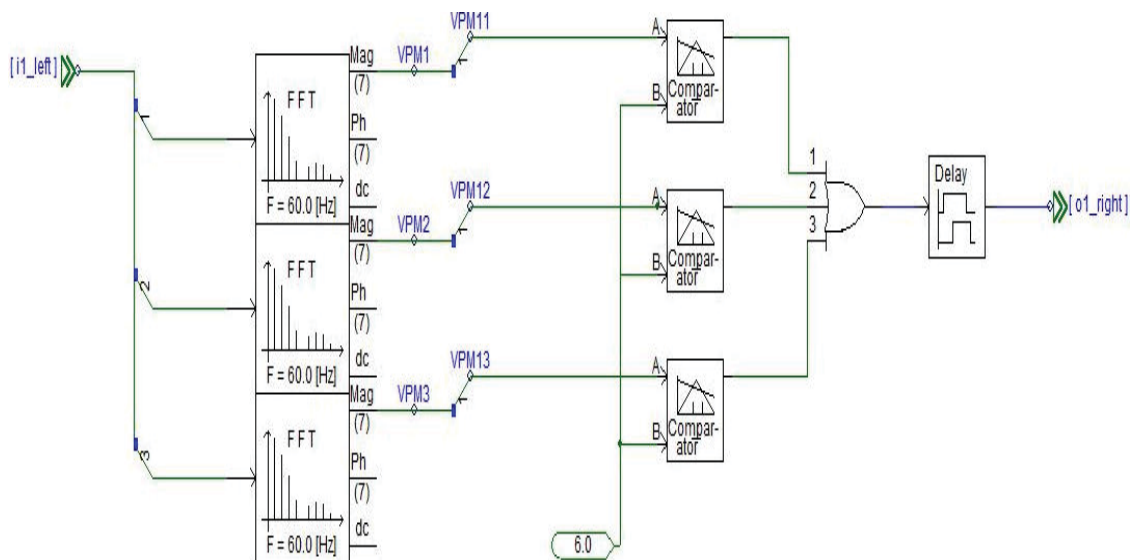


Fig. 3 Control signal to commence measurement

The directional element is reset when the control signal goes low. This system preserves the directional signal beyond the time delay when the fault is not cleared and control signal remains high for more than one cycle. The initial and delayed current and voltage signals are used to calculate the phase difference.

The initial voltage and current phasors are passed to Relay1 block in PSCAD as shown in Fig. 4. The input signal is delayed by one cycle to preserve the initial value under fault conditions. The fault and the pre-fault signal is passed to voltage angle block (angle1) to calculate the voltage phase difference. Similarly, current fault and pre-fault value are passed to current angle block (current angle). The difference

in voltage angle and current angle is used to calculate the fault direction.

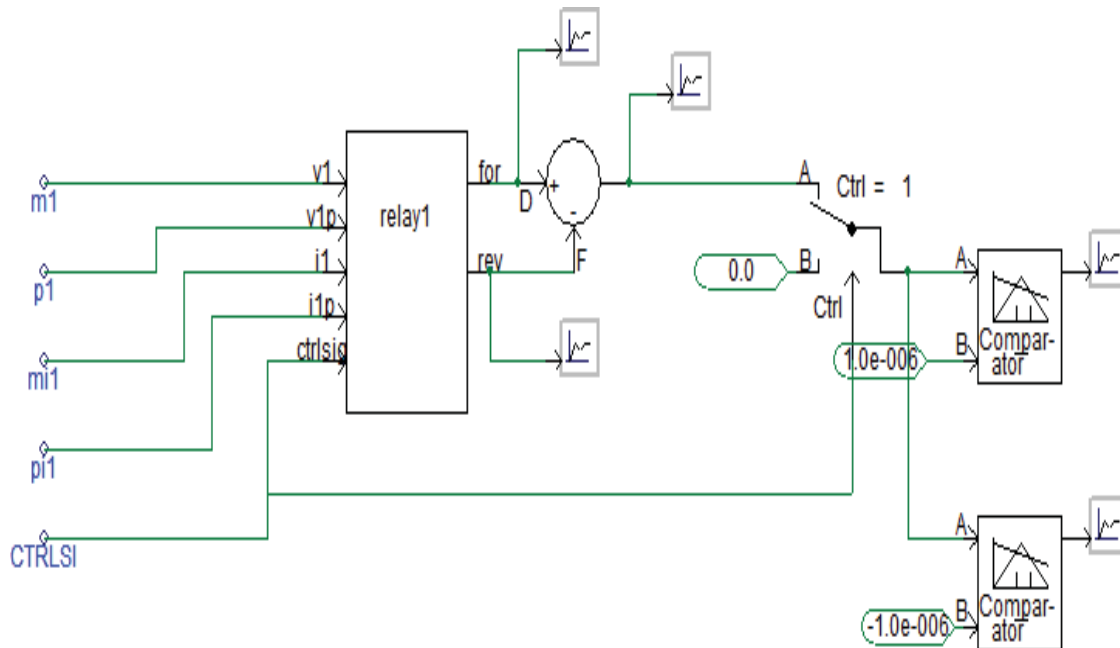


Fig. 4 Positive directional element in PSCAD

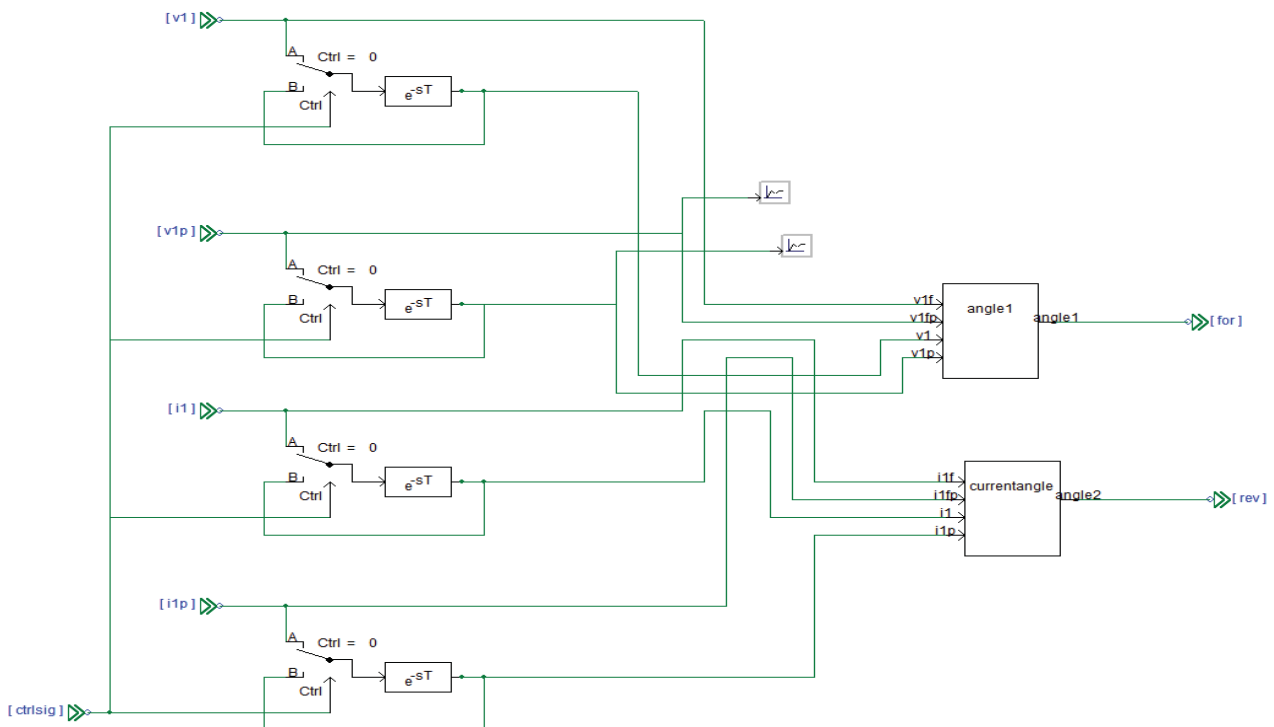


Fig. 5 Voltage and Current phase angle block in PSCAD

IV. RESULTS IN PSCAD

Future Renewable Electric Energy and Management (FREEDM) loop is a 12.47 kV distribution system with

integration of renewable energy and storage devices. The FREEDM loop is shown in Fig. 6.

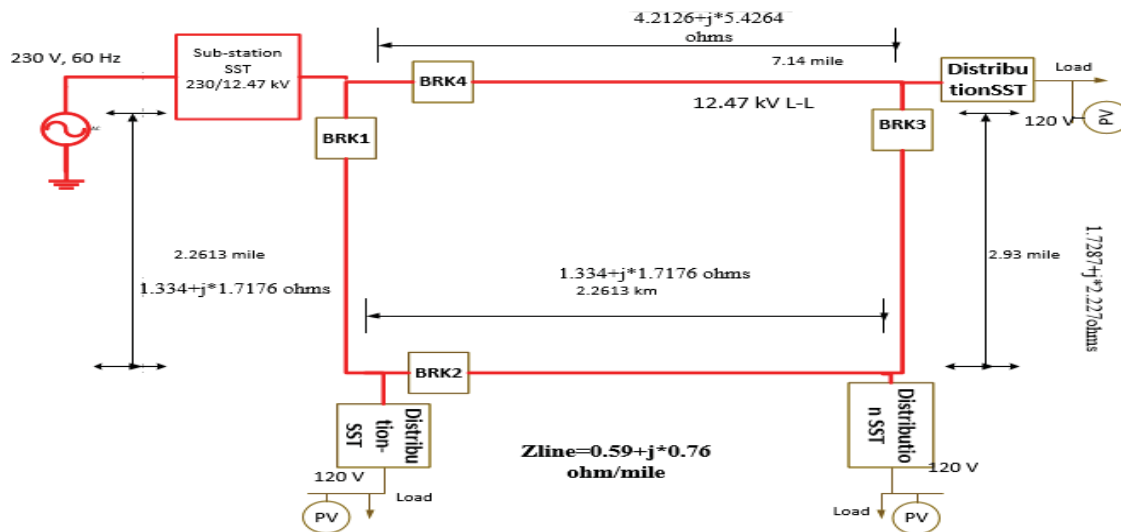


Fig. 6 FREEDM loop system

A simple radial system was built in PSCAD and various cases of line to ground faults, double line to line and double line to ground were simulated. For this case, the forward

impedance element of Relay1 and the reverse impedance of Relay2 should go high as the fault is located in between the two relays.

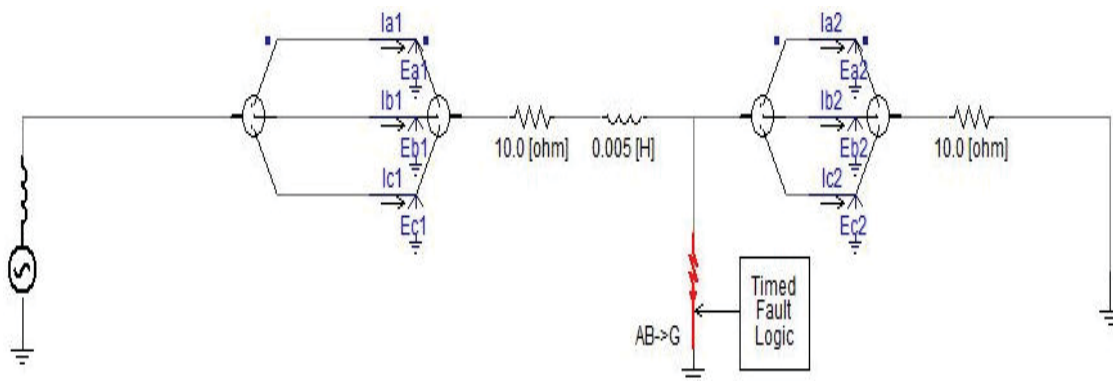


Fig. 7 Radial system model in PSCAD

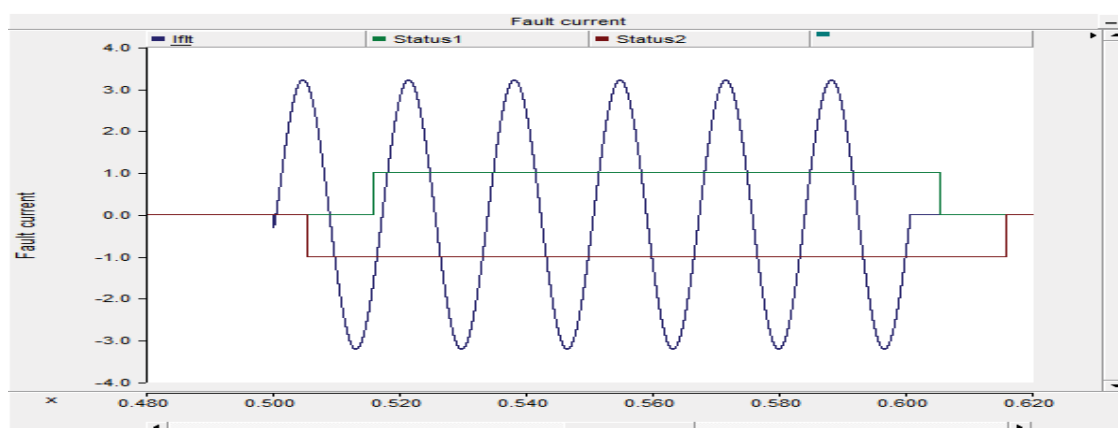


Fig. 8 Waveform of fault current and status of impedance element of Relay1 and Relay2 for asymmetrical fault

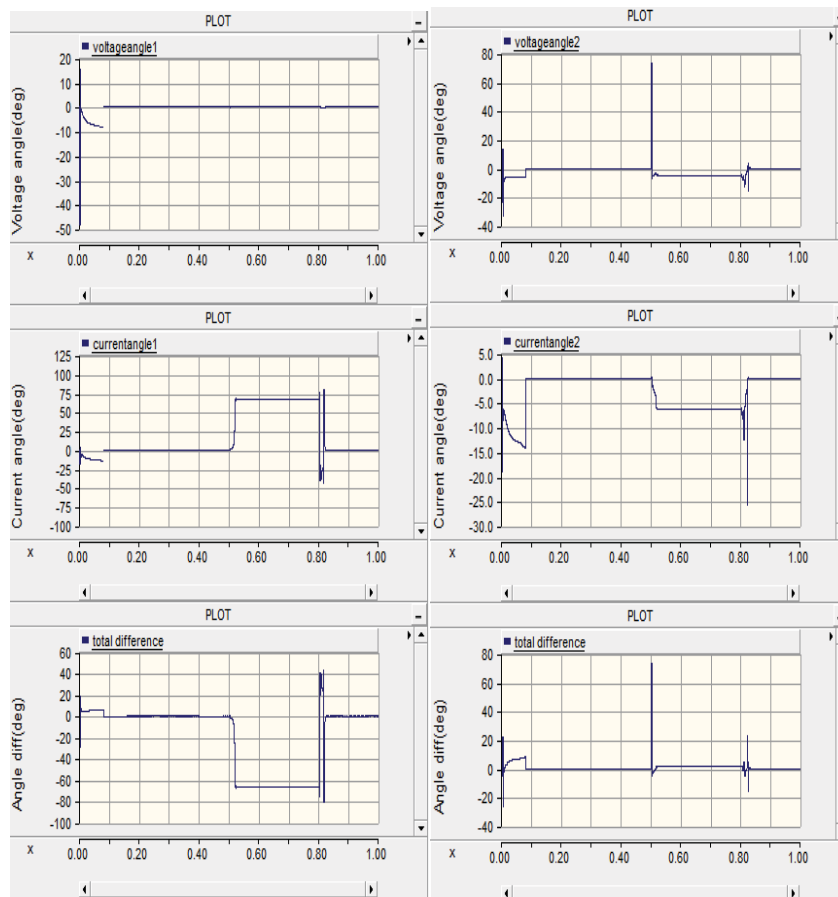


Fig. 9 Plot of voltage angle, current angle and total difference in phase angle for Relay1 and Relay2 for symmetrical fault

TABLE I
TRIP SIGNAL DELAY FOR VARIOUS FAULT ANGLES

Fault Incident Angle (degrees)	Trip Time (milliseconds)
10	18.23
20	19.41
40	18.32
60	18.14
90	18.75
120	18.81
150	18.65
180	17.75
200	18.65
220	18.19
240	17.70
260	17.75
300	17.90
320	18.05
335	18.10
350	18.35
360	18.45

From waveform it can be seen that the impedance element of Relay1 is +1 and impedance element of Relay2 is -1 which shows that the fault is in between Relay1 and Relay2. Relay1 takes more than one cycle for breaker opening signal while Relay2 takes less than one cycle. The sensitivity of the

operation can be increased depending on the threshold value of the negative sequence current.

In Fig. 9, for a fault between Relay1 and Relay2, the total difference in angle for Relay1 is negative indicating forward fault while for Relay2 is positive indicating the reverse fault. Hence, this confirms that the fault is between Relay1 and Relay2.

Table I shows the average trip delay time obtained for the various fault incident angle. The trip delay is minimum at the zero crossovers.

V. HARDWARE IMPLEMENTATION

Commercial available SEL-3031 radio link was used to establish communication between the two relays. The radio link prevents the need for multiple sets of radio or expensive dedicated fiber transmitting over the long distances. The SEL-3031 radio link can simultaneously communicate with up to three independent ports and protocols via point-to-point radio operation. The SEL Mirrored bit technology was used to set up communication between the two radio links, as in [10].

Commercial Schweitzer relay SEL-351S and Radio Link SEL-3031 was used to implement the pilot directional algorithm. Fig. 10 shows the single line diagram of a three phase test bed used for hardware implementation. During

setting the radio link in the laboratory various factors were studied to ensure the reliable communication. The important factors for digital radio are the distance between transmitter and receiver, obstructions in the line of sight between antennas, and the natural environment beneath the path.

The operation of radio is limited by line of sight. The line of sight between the two antennas is shaped liked and ellipse called Fresnel zone, as in [10]. Obstructions in the Fresnel zone may cause multipath interference due to reflective or refractive signals that may arrive at the receiver out of phase

with the desired signals. For the laboratory purpose, SEL recommended the use of Yagi antenna (directional antenna). Directional antennas confine the transmission and reception of signals to a relatively narrow lobe, allowing greater communication range, and reducing the chances of interference to and from other users outside the pattern.

A 10 ohm resistor and 5 mH inductor connected in series were used to represent the line impedance of a feeder with a load of the 10 ohms resistor.

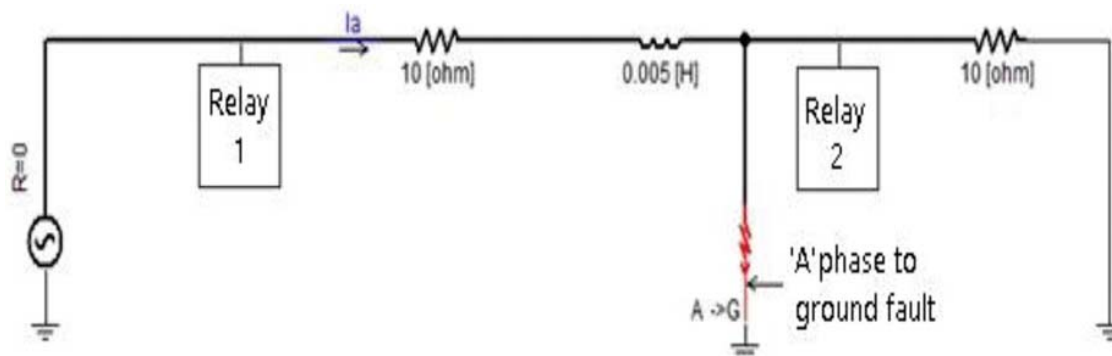


Fig. 10 Single line diagram of the hardware test bed

A three phase 208V, 60Hz was used as the power supply. A SLG fault was applied using 'fault switch' as shown in Fig. 10 with a fault resistor of 10 ohms. The current transformer used for relay one was installed with a ratio of 100/10 while relay two was installed with 100/5 CTs. 1:1 isolation transformers were used as voltage inputs to both the relays. SEL-3031 serial radio transceiver was used as a communication device with wireless communication as the medium between the relays. The hardware setup is shown in Fig. 11. The current in the test bed jumped from 7 A to 8.5 A under the fault.

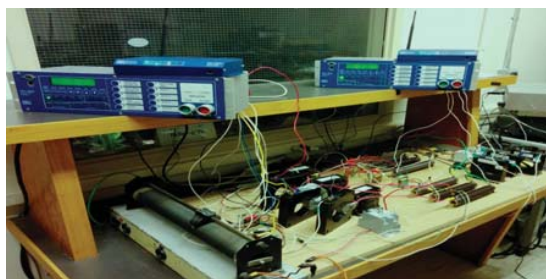


Fig. 11 Hardware setup at ASU power system lab

The relays calculate the negative sequence impedance to determine the direction of fault current. Mirrored bit communication was the protocol used for communication between the relays. Since the test bed used was a radial system, the fault current direction is from only one end. The forward element of Relay1 (F32Q) was compared with the reverse element (R32Q) of Relay2 to determine the fault

current direction. The F32Q element of Relay1 was transmitted as a mirrored bit to Relay2, and the R32Q of Relay2 is transmitted to Relay1. The fault was located when both of them were high.

Fig. 12 was generated using the SEL AcSELeator analytic assistant software. It shows the change in the current after the occurrence of the fault. The F32Q bit of Relay1 went high at 4.5th cycle while the trip signal was generated at 5th cycle. The time delay between the occurrence of fault and trip signal was 1.5 cycles. The relay can be made more sensitive depending on the value of pick up negative sequence current.

VI. RESULTS AND CONCLUSIONS

The trip signal delay was minimum when the fault occurred at zero crossovers. The wireless mode of communication was effective for sharing the information between the adjacent relay. The use of wireless communication for pilot protection scheme is successfully demonstrated in this paper. The scheme can effectively detect both symmetrical and asymmetrical fault. The delay time for the asymmetrical fault was less than a cycle but for the symmetrical fault, the delay time was more than a cycle. This is not a problem as the symmetrical faults are rarest of rare faults. The time delay can be reduced for the symmetrical faults if the direct comparison of the phase difference of the fault voltage and current is done.

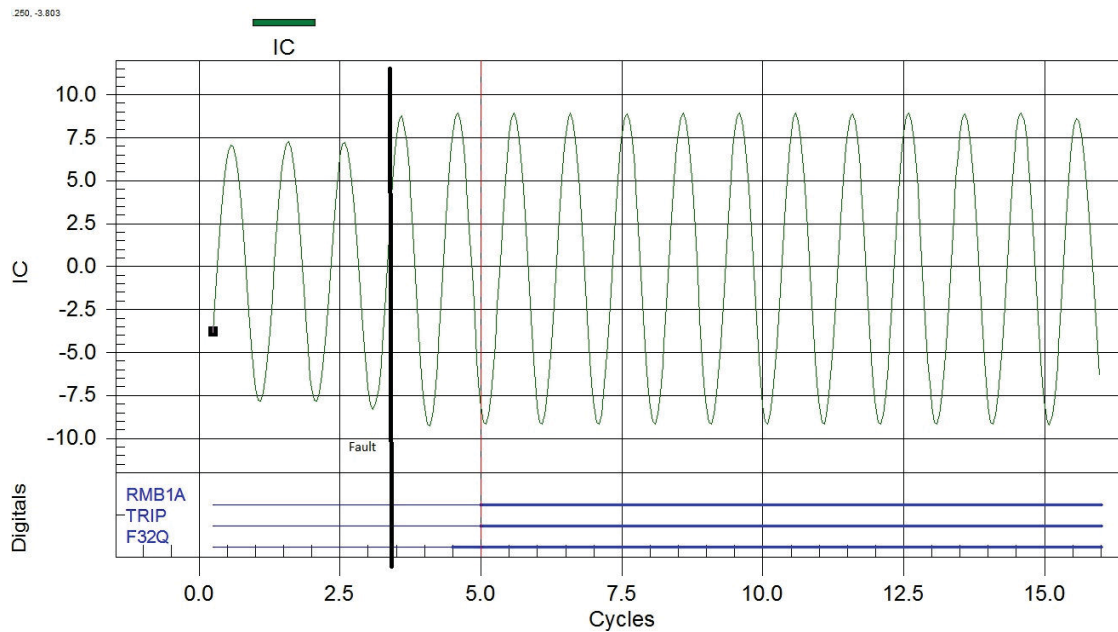


Fig. 12 Trip signal from AcSELeRator quickset software of SEL

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