Novel Pilot Directional Protection

for the FREEDM Smart Grid System

By

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ABSTRACT

The presence of distributed generation in high renewable energy penetration system increases the complexity for fault detection as the power flow is bidirectional. The conventional protection scheme is not sufficient for the bidirectional power flow system, hence a fast and accurate protection scheme needs to be developed.

This thesis mainly deals with the design and validation of the protection system based on the Future Renewable Electric Energy Delivery and Management (FREEDM) system, which is a bidirectional power flow loop system. The Large-Scale System Simulation (LSSS) is a system level PSCAD model which is used to validate component models for different time-scale platforms to provide a virtual testing platform for the Future Renewable Electric Energy Delivery and Management (FREEDM) system. It is also used to validate the cases of power system protection, renewable energy integration and storage, and load profiles. The protection of the FREEDM system against any abnormal condition is one of the important tasks. Therefore, the pilot directional protection scheme based on wireless communication is used in this thesis. The use of wireless communication is extended to protect the large scale meshed distributed generation from any fault. The complete protection system consists of the main protection and the back-up protection which are both presented in the thesis. The validation of the protection system is performed on a radial system test bed using commercial relays at the ASU power laboratory, and on the RTDS platform (Real Time Digital Power System) in CAPS (Center for Advanced

Power System) Florida. Considering that the commercial relays have limitations of high cost and communicating with fault isolation devices, a hardware prototype using the interface between the ADC (analog to digital converter) and MATLAB software is developed, which takes advantage of economic efficiency and communication compatibility. Part of this research work has been written into a conference paper which was presented by IEEE Green Tech Meeting, 2017.

ACKNOWLEDGMENTS

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Besides my advisor, I would like to thank Dr. Jiangchao Qin and Dr. Keith Holbert for being part of my thesis committee. I also would like to thank my parents and my girlfriend who have supported me throughout the entire process, both by keeping me harmonious and helping me putting pieces together. The most special thanks go to all my friends, who have given me her unconditional support through all this long process.

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CHAPTER I

A BACKGROUND TO PILOT DIRECTIONAL PORTECTION

I. Background of FREEDM System

FREEDM (Future Renewable Electric Energy Delivery and Management) is an initiative by the NSF (National Science Foundation) for the enhancement of the renewable energy generation, penetration and integration of renewable energy into power system grids [1].

The FREEDM system has the capability of operating in load change and reacting to the needs of the system. The integration of renewable energy can be used to supply the load demand as well as can be stored in DESD (Distributed Energy Storage Devices). The FREEDM system has advanced power electronic technologies with information sharing technology to develop a modern smart grid. The DRER (Distributed Renewable Energy Resources) takes care of the renewable energy integration, and DESD is used to store energy when supply is sufficient but demand is low. The DRER, DESD, and loads are managed with DGI (Distributed Grid Intelligence), which is the brain of the FREEDM system [2]. The system also has novel power electronic devices, FID (Fault Isolation Device), which have asymmetrical current breaking capacity and can clear faults in microseconds. The SSTs (Solid State Transformer) are one of the main features of this system. They have replaced conventional 60 Hz power transformers with a new power electronic power processing package. The SST is a cascaded rectifier, dual active bridge converter, and inverter. It has an input of 7.2 kV and output of 120 V AC (single phase), 208 V AC (three phase) and 400 V DC.

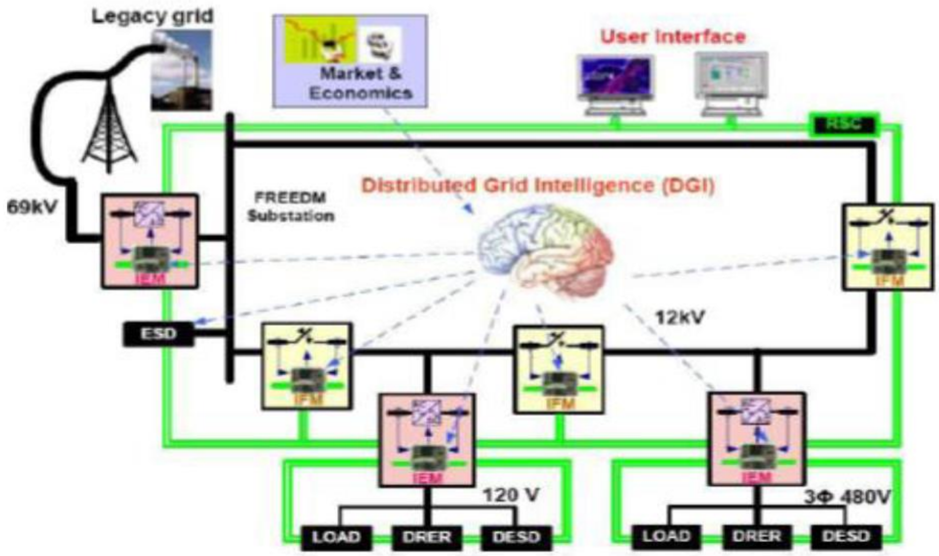


Fig 1.1. FREEDM System Diagram [3]

The FREEDM loop is shown in Figure 1.1. SST is a three-level device which has AC-DC/DC-DC/DC-AC stage, and it can allow the bi-directional flow of power. The substation SST is rated at 6 MVA, 230 V/12.47 kV, and it supplies power to the FREEDM loop. The distribution SST is rated at 12.47 kV/ 120 V. The DRER and DESD can be directly connected to the DC link of the distribution SST. The protection scheme will detect a fault in the loop and activate the trip signal to FIDs. All the coordination between FIDs and SST are done with the help of DGI through RSC (Reliable and Secured Communication Network) [3].

II. Background of Protection System

A protective relay is a device designed to trip a circuit breaker when a fault is detected.

[4] The first protective relays were electromagnetic devices, relying on coils operating on moving parts to provide detection of abnormal operating conditions such as over-current, over-voltage, reverse power flow, over-frequency, and under-frequency. [5]

Over-current protection is the most frequently used protection in which the relay picks up when the magnitude of current exceeds the pickup level. Over-current protection has the following types [6]:

1. Instantaneous over-current protection, it allows the relay to operate immediately when the measured current is larger than the pick-up current;

2. Definite-time over-current protection, it takes place after a small interval of time from the incidence of current that causes action;

3. Inverse time over-current protection, the trip time is approximately inversely proportional to the smaller values of current causing operation and tends to definite minimum time as the value increases without limit. The operating time of an inverse time over-current relay for a particular setting and magnitude actuating quantity can be known from the characteristics supplied by the manufacturer. The typical characteristics are shown in Fig. 1.2.

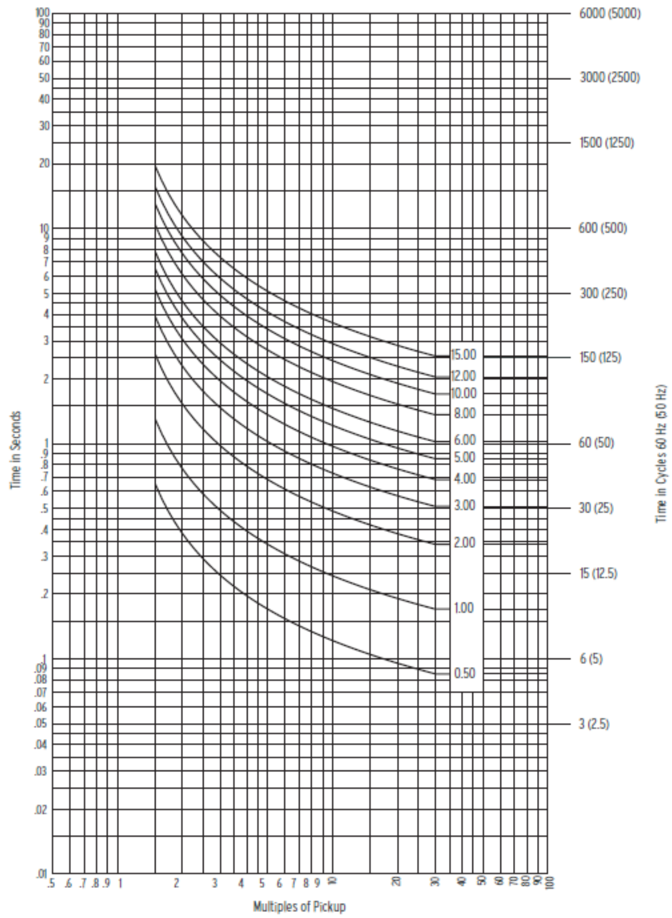


Fig 1.2. Inverse Time Over-current Curve [7]

An inverse curve is one in which the operating time becomes less as the magnitude of the actuating quantity is increased. However, for higher magnitudes of actuating quantity the time is constant.

Differential protection is commonly used to protect generators, buses, and transformers. [8] The principle of the differential protection is considered superior with respect to selectivity, sensitivity, and speed of operation as compared with directional comparison, phase comparison, or stepped distance schemes. The differential function responds to the sum of all the currents of its zone of protection. Ideally, this sum equals zero under all events except for internal faults. Practically, measurement errors and shunt elements inside the zone may create a spurious differential signal, calling for adequate countermeasures. These countermeasures become more sophisticated with advancements in the field of differential protection and progressed from adding an intentional time delay, percentage restraint, and harmonic restraint and blocking to sophisticated external fault detection algorithms and adaptive restraining techniques. [9] A typical example of the practical application of differential protection system is presented in Figs 1.2, 1.3, .1.4.

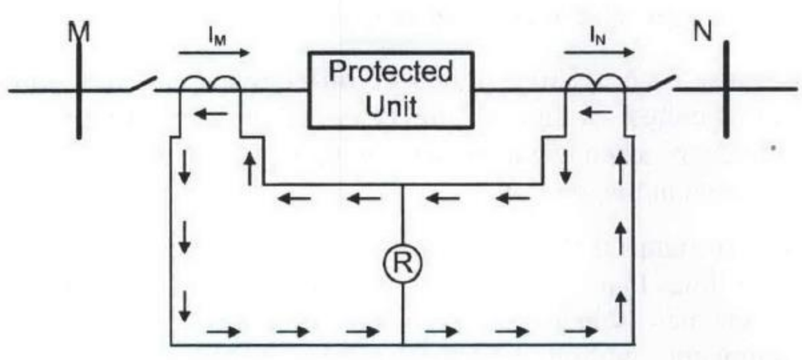


Fig 1.2. Normal Condition [10]

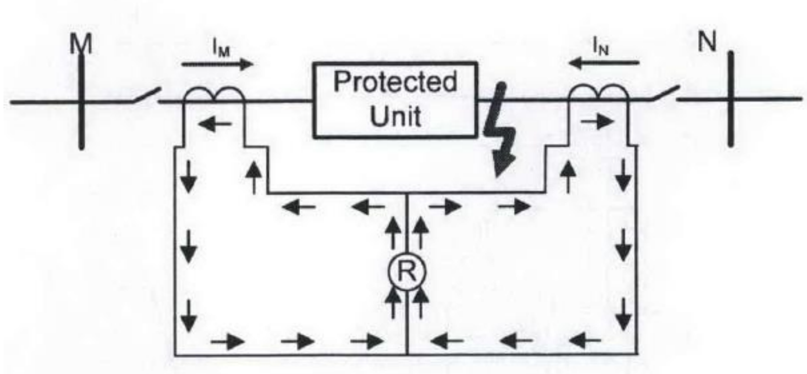


Fig 1.3. External Fault Condition [10]

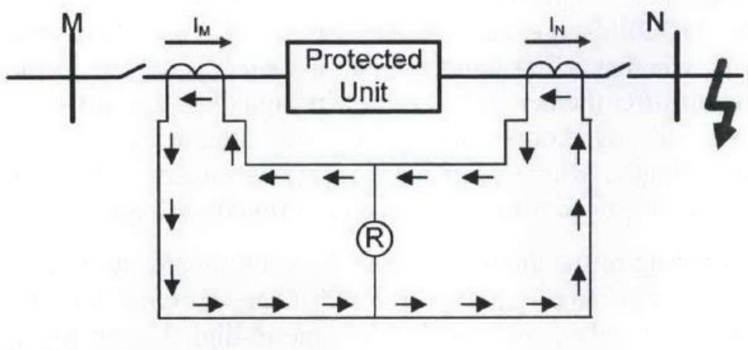


Fig 1.4. Internal Fault Condition [10]

When there is no fault or the fault is out of the protection zone, the direction of the current remains the same, when the fault occurs in the protection zone, the direction of the current has been changed. By comparing the directions of the current on both sides, the fault location can be determined.

III. Literature Review

Former ASU students have developed a protection method for the looped system without communication from multiple sources [11]. The directional relays with time-inverse overcurrent characteristics were used to detect the fault in the system. However, the method cannot provide accuracy and speed for the protection system because the trip time of the time-inverse overcurrent protection depends on the magnitude of fault current.

A pilot wire differential protection scheme for distribution systems is discussed in [12]. The differential scheme makes the use of the pilot wires where information is transferred with the help of communication link. The system can be classified into a different type of protection system based on the type of communication link used for information sharing.

A protection system using square wave is mentioned in [13]. A GPS synchronized protection system is used to detect the fault. The system is divided into various sections. Each section has a multi-terminal differential protection system, which adds up the GPS-synchronized current in the section. If the section current is larger than the threshold value, then this section is where the fault occurs.

A design and implementation for fast pilot protection scheme is described in [14]. The time stamped signals are converted to digital format and transmitted to data acquisition devices using communication link. The processing unit compares the measured data and makes a decision. The scheme is based on a pilot protection algorithm with overcurrent protection. It is found to be faster compared to the conventional differential protection system because of the overcurrent protection scheme. The average trip time is about five milliseconds. However, this system suffers from the problem of time synchronization. If any error or delay occurs in one of the synchronization channels, the feasibility of this type of system would be limited. The designs and limitations of using directional element models have been discussed in [15].

Various laboratory and field tests are presented to examine the limits of sensitivity and other conditions like loss of voltage, loss of power. The designs of directional element continue to evolve with the changing power scenario. A comparison of electromechanical relays and modern digital relays is presented. The sensitivity analysis is one of the most important factors to understand the behavior of relay. Although automatic settings of the modern relays are helpful, the proper application of these configurations is necessary to maintain reliability and flexibility.

The protection scheme for the closed-loop system is presented in [16]. The flexibility of closed loop system has been increased using intelligent electronic devices. The power flow could be bi-directional. The closed loop system has significantly improved the availability of power and quality of power. The coordination of relays in closed loop system is essential to maintain reliability and quality of power. In radial system, the protection scheme can be divided into overcurrent scheme and time overcurrent protection scheme between adjacent relays. The same method cannot be used for loop system. The use of directional element along with overcurrent relay is standard practice for loop system.

One directional current protection scheme utilizes both a voltage transformer and a current transformer that are both wired to the digital relay on one side such that the relay can act as a wattmeter [17]. This will allow the voltage and current to multiply so the phase difference between the two values can be extracted. If the current is lagging the voltage by up to 180 degree, the switch will close causing the coil to energize and trip the circuit. If the current was leading the voltage by up to 180 degree, the relay will not close the switch and the breaker will not trip. The phase in which the current leads or lags the voltage will be dependent on whether the fault is located to the left side of or the right of the voltage transformer. This is useful in shutting off the side of the circuit that is faulty to not impede the operation of the entire circuit.

The distance protection also uses both voltage and current transformers to react to circuit fault, which is faster than an overcurrent protection relay [18]. This is because the relay takes the voltage to the current ratio, when the current rapidly increases; there will also be a rapid decrease in the voltage. If the current becomes two times of the former value while the voltage decreases to the one-third of the value, this means that the impedance protection scheme will detect an impedance change in the circuit which is six times the original value. This is much larger than detecting current values, so the relay will be much more responsive in detecting faults. This impedance relay has a “reach” characteristic that identifies how far down the line the relay detects faults. They are usually set to 80%, 100% and 120% down the transmission line for different zones. For the closest zone, the time delay is smaller than the zone that is further away. This will prevent multiple relays from turning off for a single fault.

Non-faulted parts of the power system should not be affected by faults outside its zone of protection [19]. The distance protection is not recommended for short lines without communication. The use of communication channel makes directional overcurrent protection attractive for short lines. It has fast tripping speed compared with distance protection. The use of digital channels for pilot relaying due to higher data transfer rate, reliability is on the rise. A discussion on the requirements of communication channel for joint pilot schemes is discussed in [20]. The issues related to channel asymmetry and channel switching has been addressed. The widespread use of point-to-point connections for pilot relaying seems to be logical instead of replacing a dedicated relay channel. The fiber-optic gives fast and error-free point-to-point connection, but channel interruption due to fiber cut is a grave concern of utilities. The use of wireless communication is appealing in terms of reliability and security.

A new scheme is developed with directional relays where fiber-optic communication is shown in [21]. This protection system eliminates the use of a central controller for decision making and hence it is fast enough to detect the faults. Although the scheme is quick enough to detect the faults in the system, it suffers from the reliability issues. The fiber-optic cable is not a perfect solution for the long-distance communication because the expensive cost.

Normally, over current or distance protection schemes are designed as back-up protection, the faulty section is normally isolated discriminatively by the time grading. The overcurrent protection systems need to be considered as back-up protection because most of them are designed for radial distribution system with unidirectional power flow while the FREEDM system supports bidirectional flow of power. [1]. The distance protection is also not a good choice for the loop system because the protection coverage zones are defined for distance relays but they suffer from the problem of under reach the protection zone and over reach the protection zone. It is also difficult to determine the fault location while using the distance protection in a loop system because the loop system supports bidirectional power flow. [22] A pilot back-up protection based on the communication channel for the substation is introduced in [23], the protection scheme is based on the distance protection, a communication channel is added to send trip signals. A new current differential back-up protection using RTDS processor for closely coupled distribution systems is used in paper [24], the availability, flexibility and programmability of the RTDS allowed a realistic evaluation of the functions of a proposed wide area current differential back-up relay by emulating the relay on a processor in the simulator.

A system [32] is modeled in the Electromagnetic Transient Direct Current Analysis (EMTDC) and several cases were created based on the information contained in the traveling voltage and current waves. By comparing the reflection and refraction of the traveling waves, a hardware platform is implemented with a DSP module and a personal laptop, a real-time operating system is used to load the code on the processor.

Paper [33] proposes a low-latency hardware digital multifunction protective relay on the Field Programmable Gate Array (FPGA). Taking advantage of inherent hard-wired architecture of the FPGA, the proposed hardware relay achieves low latencies in various relay modules which are developed in hardware description language. Voltage protection, directional protection and frequency protection are realized by the proposed hardware.

Paper [34] describes a hardware prototype of the fault direction identification scheme, the transient classification system is implemented and tested under different practical scenarios using input signals generated with a real-time waveform playback instrument. The prototype successfully demonstrates the potential of using transient signals embedded in currents for detection, localization and recognition of faults in transmission networks in a fast and reliable manner.

IV. Objective of Research

The bi-directional flow of power in the FREEDM system limits the use of conventional protection scheme for the system protection. Moreover, the loop system has massive power electronic power devices which are used to control power flow and limit fault current. Thus, these systems are more sensitive to fault and power oscillations. The conventional overcurrent protection scheme doesn't work in FREEDM system. Hence, the protection system must be modified for the loop system without sacrificing speed and selectivity of the scheme.

In addition to design and validation of the main protection for FREEDM system, a reliable back-up protection needs to be developed during the communication failure of the main protection. DGI would not be able to communicate with the FIDs as the trip time is not fast enough. Hence, the implementation of this scheme would take away the smart grid factor from the system.

A protection system with wireless communication scheme is used in this thesis. The directional overcurrent based relay is used to detect and sectionalize the faulty section from the healthy system. The wireless communication has comparable speed and selectivity with fiber optic communication.

V. Organization of Thesis

Chapter II presents the introduction of the pilot direction protection system. The combination of negative sequence and positive sequence based directional element for fault detection is discussed. Chapter III presents the validation of the pilot directional protection in the FREEDM loop using RTDS system using the low-voltage interface panel of the digital relay. Chapter IV presents the back-up protection for the loop system based on wireless communication, when the main protection didn’t work, the back-up protection will clear the fault after several cycles later. Chapter V introduces a hardware prototype using the interface between the analog to digital signal converter and MATLAB software instead of using commercial digital relays. Chapter VI presents conclusions of the thesis and future work. Appendix A presents the MATLAB code to control the data acquisition devices to process the line data and detect the unsymmetrical fault and unsymmetrical fault direction.

CHAPTER II

MAIN PILOT PROTECTION WITH WIRELESS COMMUNICATION

I. Introduction of Directional Elements

The directional protection is designed to operate for fault currents in only one direction. To achieve operation for the fault flowing in one direction, it is necessary to add a directional element to the protection system. Sequence components consist of positive-sequence, negative-sequence and zero-sequence quantities. Basically, positive-sequence quantities are those present during balanced, three-phase conditions. Positive sequence quantities make up the normal voltages and currents observed on power systems during steady-state conditions. Negative-sequence quantities are measurements of the amount of unbalance existing on a power system. Zero-sequence quantities are most commonly associated with ground being involved in an unbalanced condition. Negative- and zero-sequence quantities are usually only present in substantial levels during unbalanced, faulted conditions on a power system. [25]

A. Negative Sequence Directional Element:

Since negative- and zero-sequence quantities are only present in relatively large values for faulted conditions, they are often used to determine a faulted condition that exists on a power system.

The Negative-Sequence Directional Element is used under the circumstance of that looks at the negative-sequence voltage on, and negative-sequence current through, a transmission line and compares the relative phase angles of the two quantities. A forward fault is declared when the negative-sequence current leads the negative-sequence voltage by 180 degrees minus the characteristic angle of the transmission line. This component can be described by the following equation. [26]

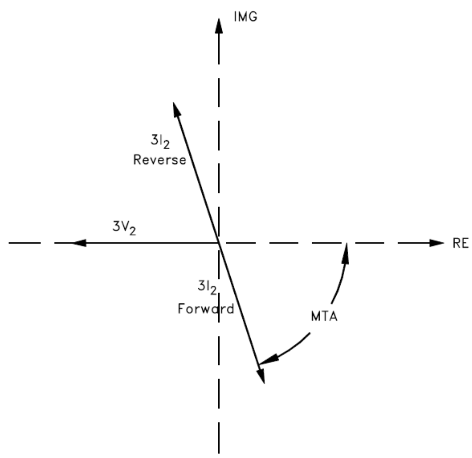


Fig.2.1. Negative Sequence Directional Characteristics [26]

$$T32Q = |V2||I2| * \cos(\angle V2 - \angle I2 - MTA) \quad (2\text{-}1)$$

Fig 2.1 shows the negative sequence directional characteristics. T32Q is the product of the negative sequence component and MTA is the impedance angle of the transmission line. A positive value indicates a fault is in the forward direction.

The negative sequence directional element could also be used to calculate the negative sequence impedance to determine the fault location. The calculated scalar quantity $Z2$ is compared with two threshold values to determine whether the fault is in forward or reverse direction to a relay. Typically, the threshold value is half of the positive sequence line impedance.

$$Z_2 = \frac{Re[V_2 \cdot (I_2 \cdot \theta_{line})^*]}{I_2^2} \quad (2\text{-}2)$$

$$V_2 = Negative\ \ sequence\ \ voltage$$

$$I_2 = Negative\ \ sequence\ \ current$$

$$Z_2 = Negative\ \ sequence\ \ impedance$$

$$Z_{2F} = Forward\ \ threshold\ \ impedance$$

$$Z_{2R} = Reverse\ \ threshhold\ \ impedance$$

$$\theta_{line} = Line\ \ impedance\ \ angle$$

$$if\ \ Z_2 < Z_{2F}, fault\ \ is\ \ in\ \ forwrd\ \ direction$$

$$if\ \ Z_2 > Z_{2R}, fault\ \ is\ \ in\ \ reverse\ \ direction$$

$$if Z_{2F} < Z_2 < Z_{2R}, there\ \ is\ \ no\ \ fault$$

The negative sequence quantities do not exist in the system during the normal operation. The calculated negative sequence impedance lies within the forward threshold and reverse threshold values. However, during a fault, sequential components come into play and $Z2$ could be used to determine the fault location. If the calculated $Z2$ is less than forward threshold impedance, then the fault is in a forward direction to a relay. If the calculated $Z2$ is greater than reverse threshold impedance, then the fault is in a reverse direction to a relay. During a symmetrical fault, negative sequence components are negligible in the system, and the directional element fails to detect the fault. Hence, to overcome this, the relay uses positive sequence components during symmetrical faults to identify the directionality of the fault current.

B. Positive Sequence Directional Element:

The use of positive sequence directional element is prevalent during three phase faults also known as symmetrical faults. Figure 2.2 shows the transmission line for the analysis of positive sequence directional element for fault detection. The positive sequence network for a forward fault F1 and reverse fault F2 is shown in Figure 2.3. The ZM1, ZL1, ZN1 are the positive sequence impedances of the source M, the line, and the source N, and ΔZ1 is a fault-type-related impedance. [27]

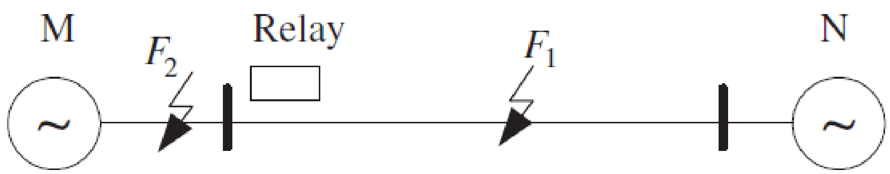
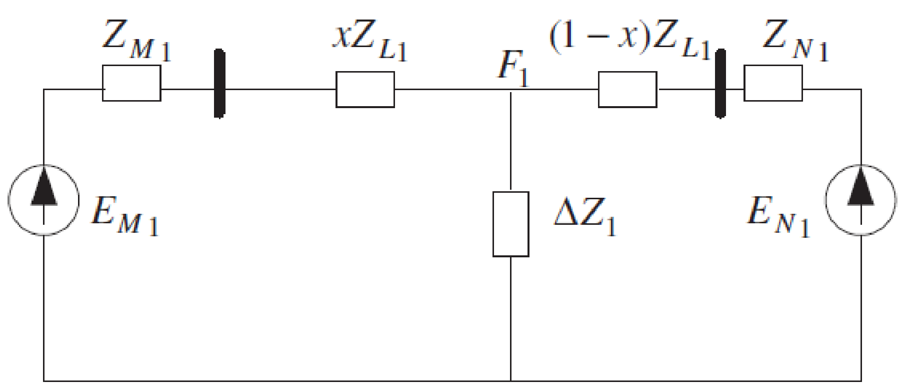
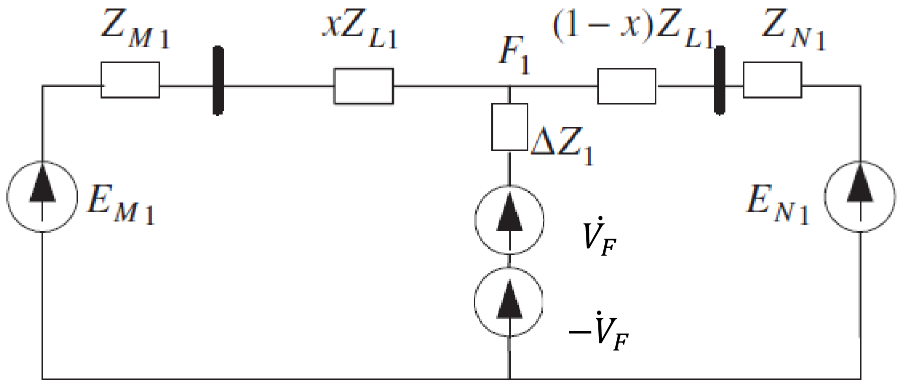


Fig. 2.2. Transmission Line Subjected to Fault



(a)



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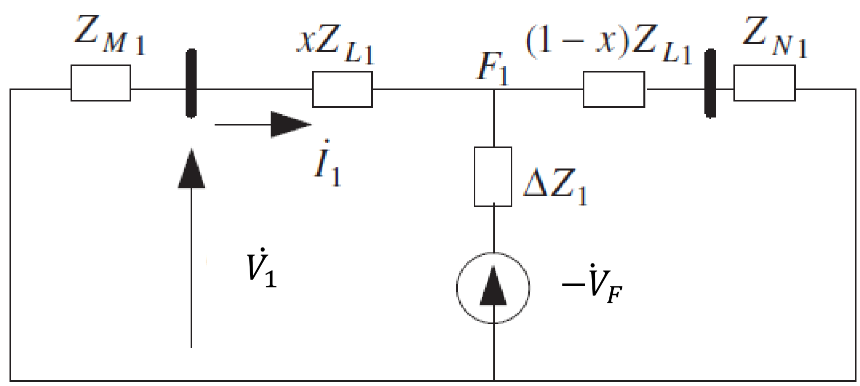
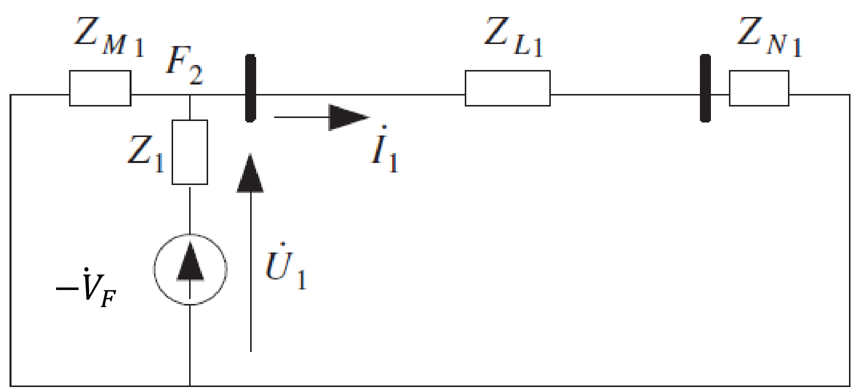


(c)



(d)

Fig. 2.3. Decomposition of Positive Sequence Network [27]

The circuit shown in Fig. 2.3(b) is the equivalent network of Fig. 2.3(a), where $\dot{V}_F$ is the pre-fault voltage at the fault point. By applying the superposition principle to Fig. 2.3(b), the positive-sequence fault components network (the fault-generated state) can be derived, as shown in Fig. 2.3(c). By replacing all other independent voltage sources with a short circuit, the $-\dot{V}_F$ is called the fault-source voltage, which is opposite to the pre-fault at fault point. Similarly, the positive-sequence fault components network is shown in Fig. 2.3(d).

For a forward fault, and regarding Fig.2.3(c), the voltage at the relay location is

$$\dot{V}_1 = -\dot{I}_1 Z_{M1} \tag{2-3}$$

For a backward fault, the voltage is

$$\dot{V}_1 = -\dot{I}_1(Z_{M1} + Z_{N1}) \tag{2-4}$$

Since the positive-sequence impedances are predominantly reactive, the phase relationships between voltage and current at the relay location are

$$arg\frac{\dot{V}_1}{\dot{I}_1} = -90^{\circ} or\ \ 270^{\circ} \text{for forward fault} \tag{2-5}$$

If the errors are considered which is involved in the measuring process and the sensitivity of the relay, the directional criterion for a forward fault is designed as

$$180^{\circ} + \theta < arg\frac{\dot{V}_1}{\dot{I}_1} < 360^{\circ} - \theta \tag{2-6}$$

and, for a reverse fault,

$$\theta < arg\frac{\dot{V}_1}{\dot{I}_1} < 180^{\circ} - \theta \tag{2-7}$$

where θ is called the blocking angle, obviously, if θ is 0°, the criteria will have highest sensitivity or largest operating region, but may fail to identify the fault direction when the phase difference between $\dot{V}_1$ and $\dot{I}_1$ is near 0° or 180. To prevent the relay from maloperation, the blocking angle is set as $0^{\circ} < \theta < 30^{\circ}$. The setting for θ will be decided by the real conditions of the relay and the power system it protects. The typical setting is 10°. The operating characteristic of the criteria is shown in Fig. 2.4

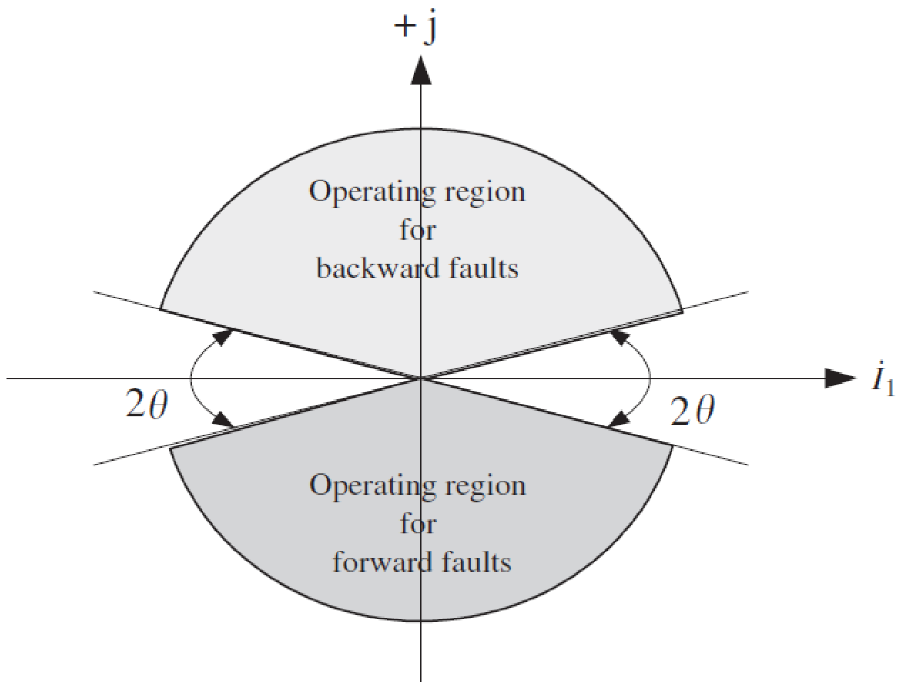


Fig. 2.4. Operating Characteristic of The Directional Criteria [27]

II. Working Principles of Pilot Directional Protection

A back-up protection scheme is developed for the FREEDM loop which could be used to detect all type of fault in the system. Fig. 2.5 shows the remote back-up protection diagram in the FREEDM loop system, the FID (fault isolation device), which is an electronic circuit breaker in the FREEDM loop, can isolate the fault. Each FID is equipped with a digital relay to collect line information and send operation signals, and the SSTs are used to replace the conventional 60 Hz power transformer with power electronic power processing package. Based on the different types of the fault, the protection system scheme can be divided into two parts, one is the detection of unsymmetrical fault the other one is the detection of symmetrical fault.

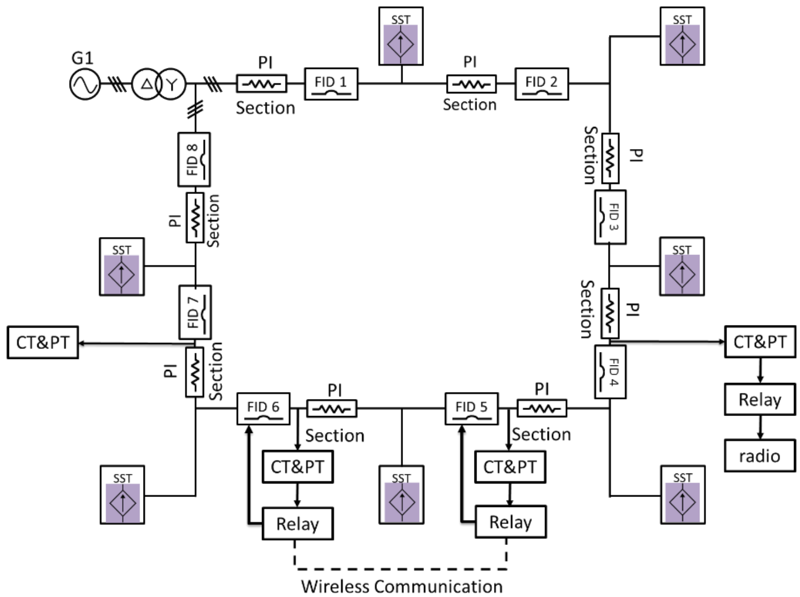


Fig. 2.5. Pilot Directional Protection Diagram

A. Detection of Unsymmetrical Faults

The complexity in designing the protection for loop system can be simplified by detecting the fault current direction. When there is an unsymmetrical fault in the loop system, negative sequence component can be detected. This method uses the negative sequence directional element to determine the direction of fault current. The negative sequence impedance can be determined by (2-2) using the negative sequence components. This calculated quantity is compared with two threshold values to determine whether the fault is in forward or reverse direction to a relay. [26]

$$Z_2=Re[V_2\bullet(I_2\angle\Theta)^*]/I_2^2$$

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 when there is a fault in loop system, negative sequential components show up and Z_2 could be used to determine the fault location. If the calculated Z_2 is smaller than forward threshold impedance, the fault is in forward direction to a relay. If the calculated Z_2 is greater than reverse threshold impedance, the fault is in reverse direction to a relay.

B. Detection of Symmetrical Faults

A scheme has been introduced to determine the directionality of fault using positive sequence. When there is a fault in the system, the magnitude and phase angle of the positive sequence component will change. The method compares with the present positive sequence components and the previous history of the corresponding positive sequence components a few cycles before. The difference in the positive voltage and positive current is used to determine the direction of fault current in the system. The calculation is shown below. [27]

$$\Delta V_1 = V_{1f} - V_{1prefault} \quad (2\text{-}6)$$

$$\Delta I_1 = I_{1f} - I_{1prefault} \quad (2\text{-}7)$$

$$\Phi = \angle\Delta V_1 - \angle\Delta I_1 \quad (2\text{-}8)$$

ΔV_1= Difference in positive sequence voltage after and before the fault

ΔI_1=Difference in positive sequence current after and before the fault

$\angle\Delta V_1$=Phase angle difference in positive sequence voltage after and before the fault

$\angle\Delta I_1$= Phase angle difference in positive sequence current after and before the fault

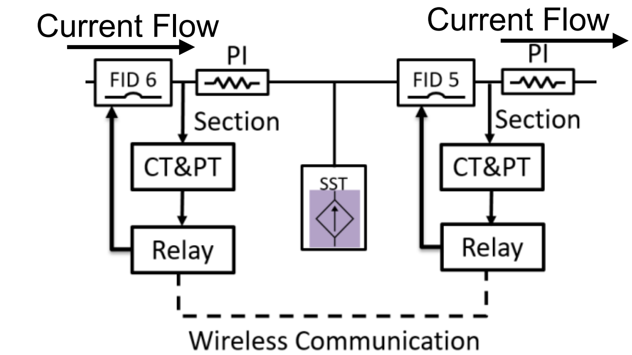
For $\Phi>0$, it is a reverse direction fault

$\Phi<0$, it is a forward direction fault

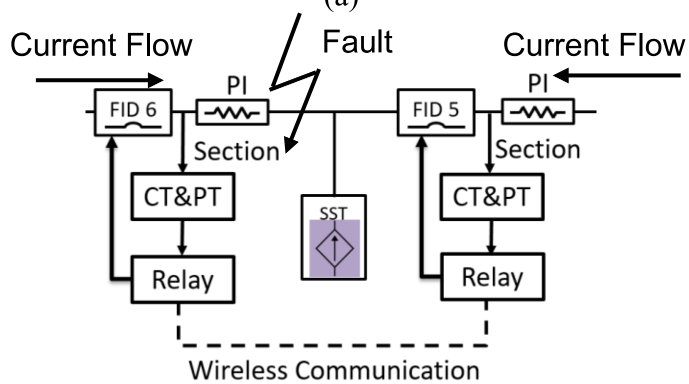
The fault location can be determined by combining both positive sequence component method and negative sequence component method. If there is a fault in the loop system, and the back-up protection is used, the digital relays will detect the fault direction and communicate with each other. If the fault happens in the protection zone, the fault direction will be opposite according to the digital relays, and both relays will send a trip signal to the corresponding FID and isolate the fault.

C. Trip Logic

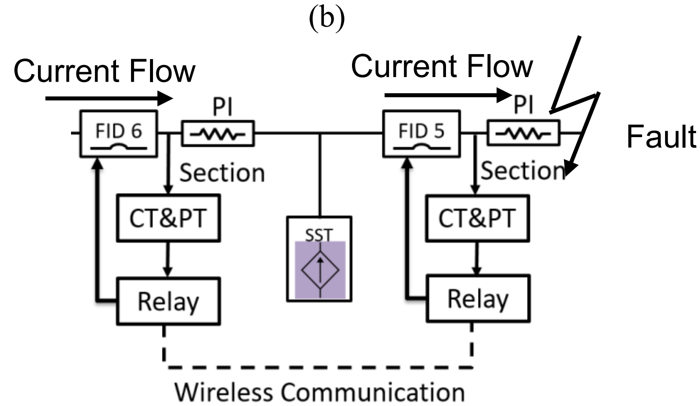
Fig 2.6 shows one section of the FREEDM loop, the trip logic is presented based on Fig 2.6.



(a)



(b)



(c)

Fig 2.6. Detailed Diagram of Protection System for FREEDM Loop

Fig 2.6(a) shows when there is no fault and every device operates normally, Fig 2.6(b) shows when the fault occurs in the protection zone and the fault current flow direction is opposite, Fig 2.6 (c) shows that when the fault is out of the protection zone the fault current flow direction is the same. The trip logic can be determined based on Fig 2.6. Table 2.1 shows the trip logic for the system, only when the relay 1 detects a forward fault and relay 2 detects a reverse fault, both relays will send a trip signal to the FID.

Table 2.1 Trip Logic for The System

	Fault direction	Fault direction	Fault direction	Fault direction
Relay 1	Forward	Forward	Reverse	Reverse
Relay 2	Reverse	Forward	Forward	Reverse
Trip signal	Trip generated	No trip	No trip	No trip

III. Wireless Communication Setup

With the increase in distributed generation and bidirectional power processing capability of modern power electronic distribution system, the directional over current scheme without implementation of pilot protection systems may not be reliable enough. Pilot wire relaying sends the digital signals over a communication link that can be used for differential protection. The most common link was copper wires that were replaced by fiber-optic and Ethernet cable. But the use of this link could increase the significant amount of delay in the system and sometimes they are expensive. The modern challenge is a method to provide digital communication for pilot protection that is reliable and affordable.

The commercial product is a 900 MHz, license free, spread-spectrum radio. It has the capability of providing DNP3 SCADA information, MIRRORED BITS® control.

The most important features of this product are:

1. Dual Radio operating modes: This supports point-to-point radio operation for distribution protection

2. Low latency: This is the most important factor for considering any communication method for pilot protection. Latency is termed as the time delay in sending information over a communication link.

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

While setting up the radio link in the laboratory, various factors were studied to ensure 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 line of sight limits the operation of the radio. The line of sight between the two antennas is called Fresnel zone as shown in Fig 2.7. Obstructions in the Fresnel zone may cause multipath interference due to reflective or refractive signals that arrive at the receiver out of phase with the desired signals. The longest communication distance of the radio in clear sight is 20 miles.

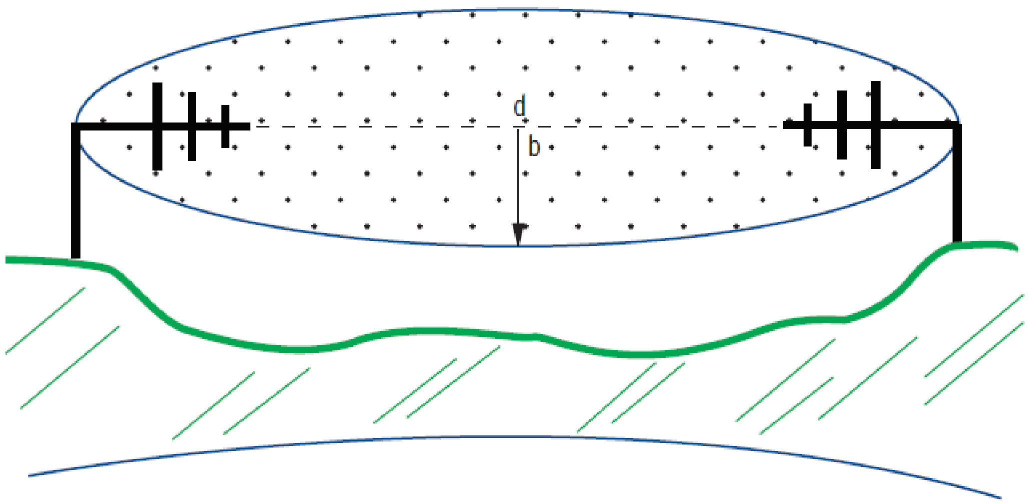


Fig 2.7. Fresnel Zone [28]

The formula used to calculate the widest distance of the Fresnel zone is as follows [28]:

$$b = 17.32\sqrt{d}/4f \qquad (2\text{-}9)$$

Where: b= radius of the Fresnel zone in meters

d=distance between transmitter and receiver in kilometers

f=frequency transmitted in GHz

Fig 2.8 shows the maximum Fresnel zone diameter and path loss for some typical path distances

900 MHz		
Distance Between Antennas	Fresnel Zone Diameter	Freespace Loss (dB)
304.8 m (1000 ft)	4.9 m (16 ft)	81
1.6 km (1 mi)	11.6 m (38 ft)	96
8 km (5 mi)	25.9 m (85 ft)	110
16 km (10 mi)	36.6 m (120 ft)	116
24 km (15 mi)	44.8 m (147 ft)	119
32 km (20 mi)	51.8 m (170 ft)	122
40 km (25 mi)	57.9 m (190 ft)	124

Fig 2.8: Fresnel Zone Diameter [28]

The path quality is evaluated in the following ways based on the test bed.

The distance between two radio links in our laboratory is around 3 feet. Hence, path quality is visually inspected. This ensures the signal strength, reliability and speed of operation.

The mirrored bit communication is the protocol used for communication between the relays. Since the test bed built for the validation is a radial system, the fault current direction is from only one end. The forward element of relay 1 is compared with the reverse element of Relay 2 to determine the fault location. Figure 2.9 depicts the communication method using mirrored bits.

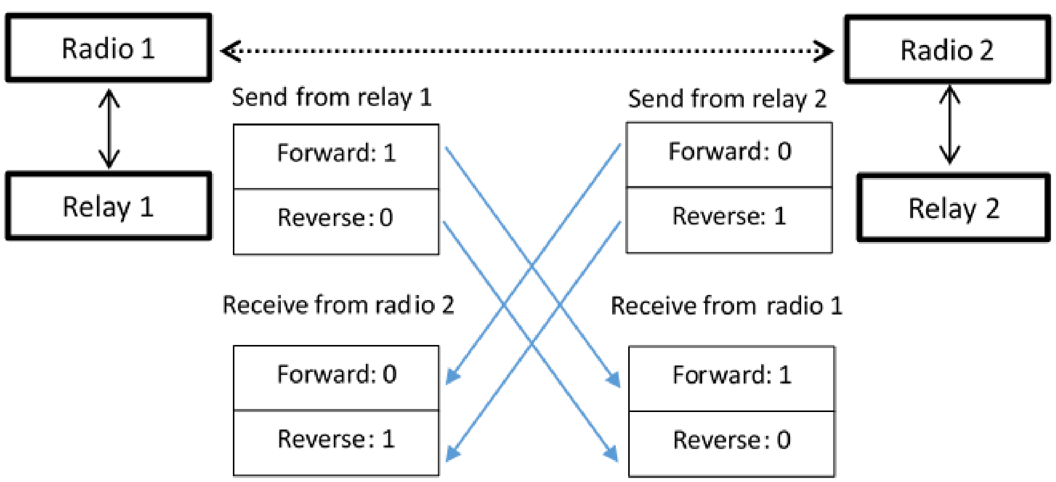


Figure 2.9: Mirrored Bit Communication in Digital Relays

The mirrored bit communication is based on the binary code string at certain length, each radio sends and receives signals in two different channels, so radio 1 will send the binary code string to radio 2 and receive another binary code string from radio 2. If the fault occurs inside of the protection zone, relay 1 will detect the fault as a forward fault, and send binary code 10 to relay 2, relay 2 will detect the fault as a reverse fault, and send binary code 01 to relay 1. Once both relays get the fault direction information via the radio, trip signal will be sent to the fault isolation device.

IV. Validation Using ASU Hardware Testbed

A. Test Bed Setup

A testbed for the validation of the protection system is built. The test consists of four parts: distribution lines, faults, two sources including feeding from network and a three-phase autotransformer respectively, and two digital protection systems consisting with digital relays, current transformers, potential transformers and magnetic circuit breakers. Fig 2.10 is the picture of the distribution line model with fault and protection system. The distribution line model is in the red square.

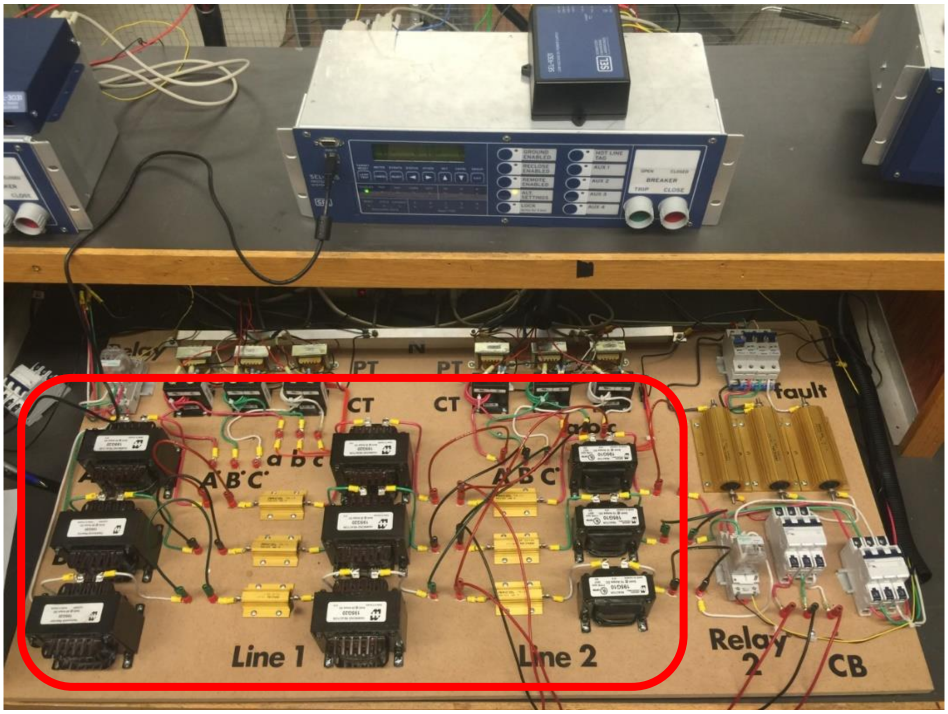


Fig 2.10. Distribution Line Model

The test bed mounted on the wooden board is to simulate the distribution line. The line is divided into two section. Line 1 is 9-mile long and Line 2 is 3-mile long, so the impedance of the two sections is different. Faults can be put in different section in the distribution line. Table 2.2 is the line data.

Table 2.2. Distribution Line Impedance

	Resistance	Inductance
Reactance from the network	0	5 mH
Line 1	5 Ohm	5 mH
Line 2	2 Ohm	5 mH

At the end of the distribution line is 120 V 3-phase supply, on the right side the transformer can change the voltage up to 144 V (120% of the nominal voltage). The voltage difference will generate current in the system. Usually the transformer voltage is set at the

90% of the nominal voltage to simulate the voltage decrease in the distribution line. Fig 2.11 shows the example output of the transformer.

Fig 2.11. Example of 110 V Output Transformer

The current transformer and potential transformer are used to measure the voltage and current in the distribution line. The protection system receives the line data and detects whether there is any fault occur in the protection zone, if the fault happens, it will send the trip signal to the relay to break the circuit. Table 2.3 shows the potential transformer and current transformer parameters.

Table 2.3. PT and CT Parameters

	Ratio
Current transformer	2:1
Potential transformer	1:1

B. Digital Relay Setup:

A commercial relay is used for detecting the fault direction, it is a programmable phasor measurement device. Some important parameters are needed for the programming, including current transformer ratio, potential transformer ratio, positive-sequence line impedance, and zero-sequence line impedance. Beside these fundamental values, the threshold values and trip logic are essential to set up. The threshold values are used for comparing with the calculated negative-sequence impedance, normally, it is half of the values of the positive-sequence impedance. The trip logic setting is the most important component for the setup, the commercial relay will send trip signal when the whole trip logic output "1". Therefore, the total trip logic is based on the Boolean calculation, the positive sequence element and negative element is connected with "OR" operation. Once the negative sequence component is detected by the relay, the negative sequence method is used and the trip logic will output "1". If the positive sequence component is different from the normal value, the positive sequence method is used and the trip logic will output "1".

C. Test Result

For unsymmetrical fault, including single phase to ground fault and phase to phase fault, negative sequence method is used. Fig. 2.12 shows current and voltage information of single phase to ground fault, Fig 2.13 shows the current and voltage information of phase to phase fault. The red dotted line shows the relay detects the fault in less than 1 cycle. The green solid line is phase A current, the blue solid line is phase B current, the red solid line is phase C current, the purple solid line is phase A voltage, the yellow solid line is phase B voltage, and the indigo solid line is phase C voltage.

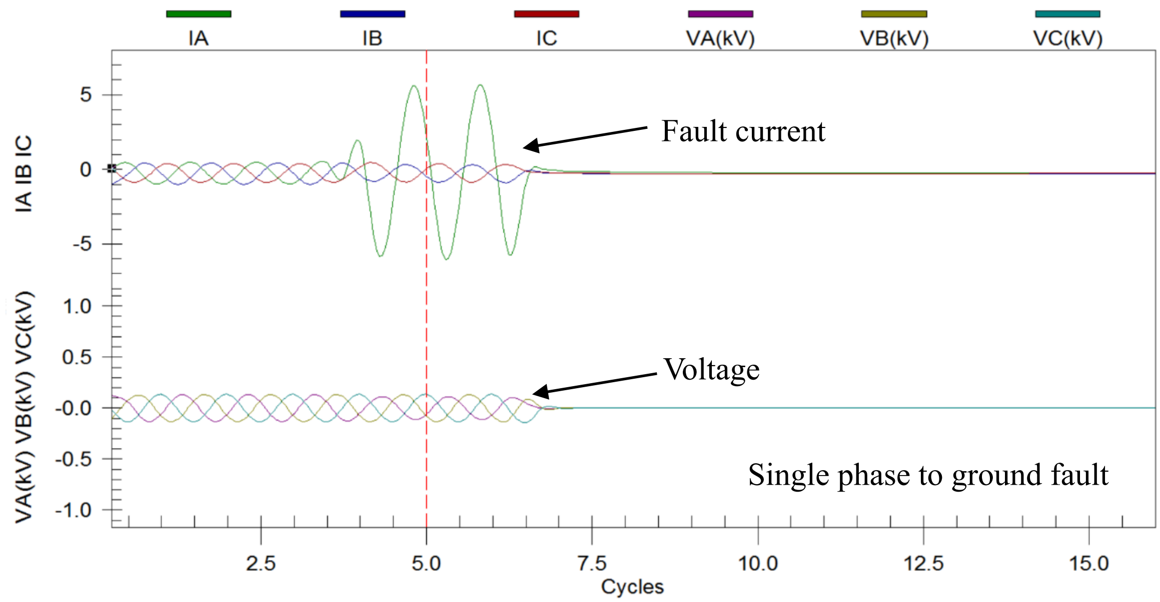


Fig 2.12. The Fault Event of Single Phase to Ground Fault

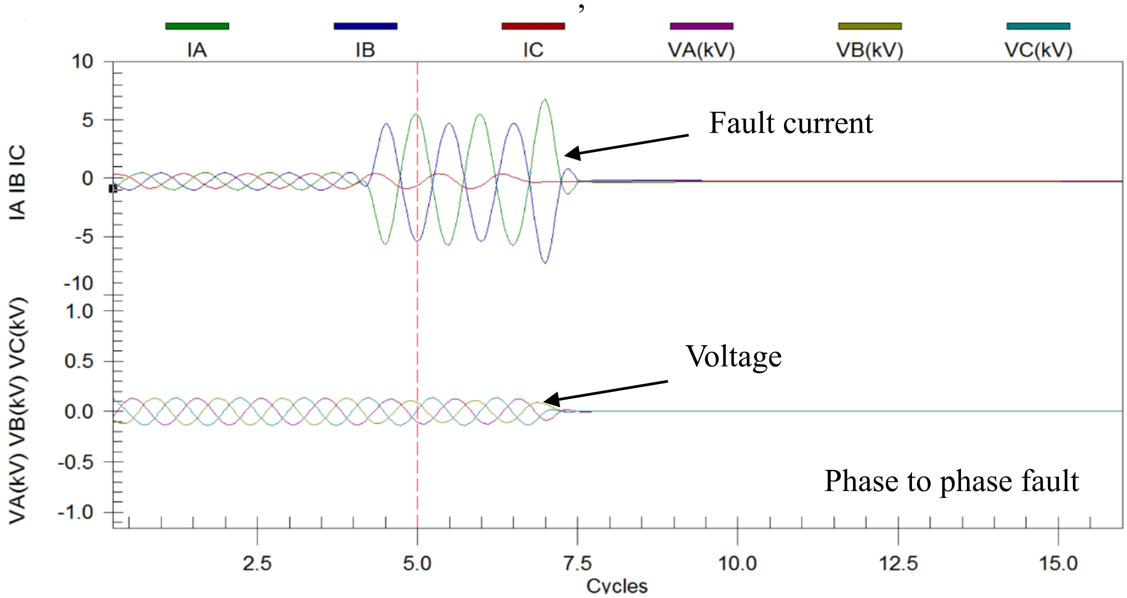


Fig 2.13. The Fault Event of Phase to Phase Fault

For symmetrical fault, positive sequence method is used. Fig 2.14 shows the current and voltage information of three phase to ground fault.

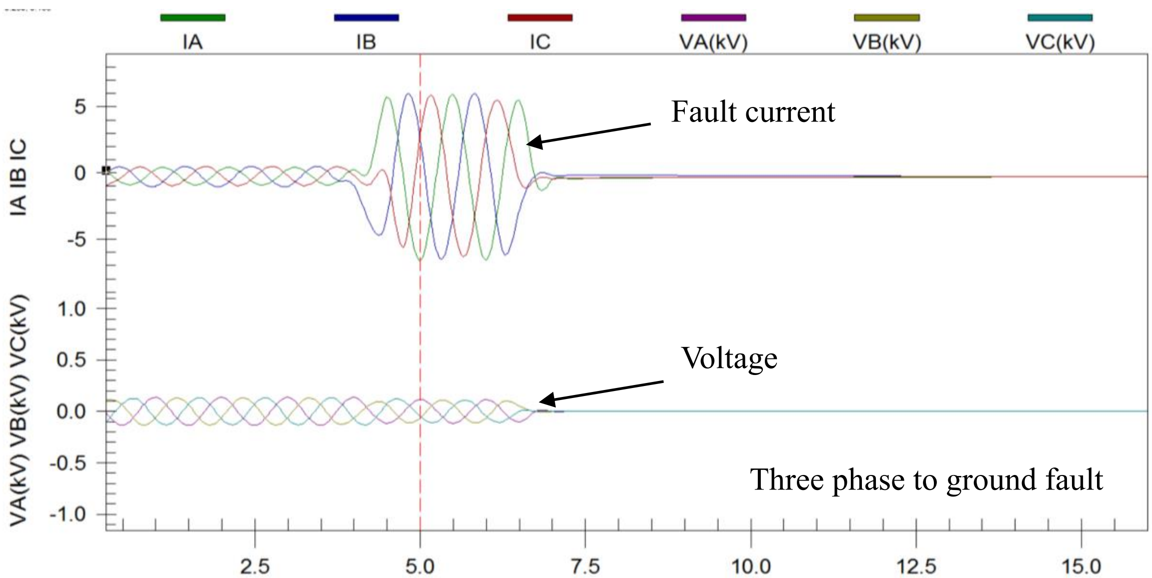


Fig 2.14. The Fault Event of Phase to Phase Fault

The time that the digital relay detects the fault is around half cycle, and the total trip time is 2 cycles.

CHAPTER III

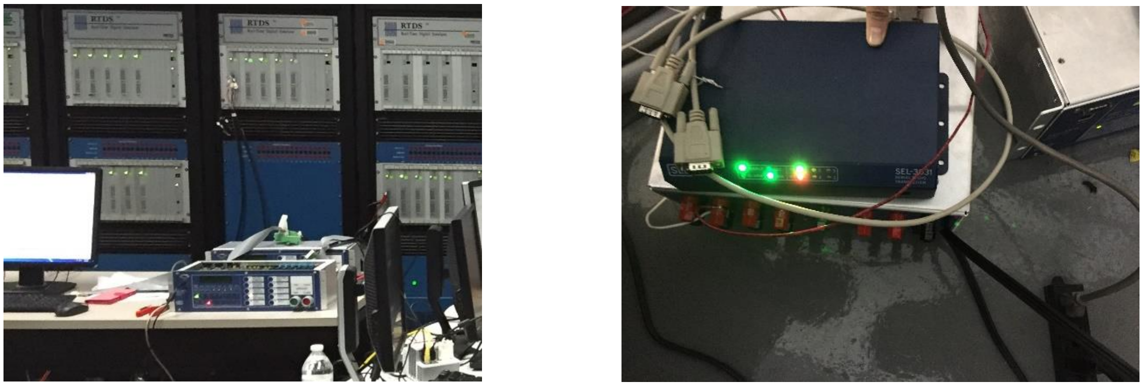
VALIDATION OF THE DIRECTIONAL PROTECTION BASED ON RTDS

I. Introduction of The Protection System

Pilot directional protection via wireless communication is designed to protect the distribution lines in the FREEDM loop system from potential faults occurring within any section of the loop. The pilot directional protection compares the direction of the terminals via communication systems. Thus, when a fault occurs in the loop, the back to back relays will exchange stage signals of fault direction, and send out trip signals once the fault location is confirmed in the protection zone. Although the reliability and accuracy of relays' communication via fiber optic had been verified by former ASU student, the huge amount of cost can be an obstacle for practical application. To reduce the expensive cost of fiber optic, the wireless communication is proposed to use, which is much cheaper than fiber optic, for pilot directional protection of FREEDM loop system.

Real Time Digital Simulator or RTDS, as the abbreviation recommended by IEEE committee, provides with simulation technology for fast, reliable, accurate and cost-effective study of power systems with complex High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC) networks. The RTDS is a fully digital electromagnetic transient power system simulator that operates in real time. It operates continuously in real time while providing accurate results over a frequency range from DC to 3 kHz. The system's graphical user interface, proprietary software and mathematical algorithms can simulate any modern electric power grid configuration. As new equipment or components are added or subtracted from the simulator's configuration, the model instantly updates.

In this test, the FREEDM loop system is simulated by RTDS, as shown in the background of Fig 3.1(a), in the Center for Advanced Power Systems (CAPS) at Florida State University. In Fig 3.1 (a), two commercial directional digital relays are interfaced with RTDS to physically detect the fault location and sent the trip signal. The input of the relays are small ac voltage signals representing secondary currents and voltages at different monitoring locations of the loop system from RTDS. The output of the relay is connected to a function block called Fault Isolation Device (FID) in RTDS in series with 24V power supply. Once FID receives trip signal from digital relay, it will cut off the fault current within the protection zone in RTDS. The digital relay builds wireless communication with other relays via SEL-3031 radio system as shown in Fig 3.1(b). SEL-3031 radio provides 9MHz mirrored bits wireless connection.



(a) RTDS and SEL-351S relays (b) Radio and power supply

Fig. 3.1. Pilot Directional Protection with Wireless Communication Configuration

This experiment tests the reliability and efficiency of the pilot directional protection via wireless communication for FREEDM loop system. First, the protection scheme is tested by placing two digital relays on both ends of one distribution line section. Both relays will communicate with each other and trip around 20 ms after the fault on average. Then a virtual relay is added in RTDS, coordinating with the two existing relays, to form two line sections between the three relays. The middle relay will communicate with both side relays. When a fault occurs in one section, only two relays on the both ends of the corresponding section will operate, leaving the third one closed. The communication for commercial radio transceiver is validated by putting the radios in two different buildings with a direct distance of around 75 meters.

II. System Setup

RTDS front panel analog output cards can send low-level voltage (analog ± 10V) to represent voltage and current in the loop system. In order to interface digital relay with the RTDS, the front case of the relay needs to be open to access to the processing module input connector (J12) and the output connector (J2) for low-level interface connection. Fig 3.2 shows the low-level test interface connector information. IA, IB, IC, IN, VA, VB, VC and GND ports are used for this test.

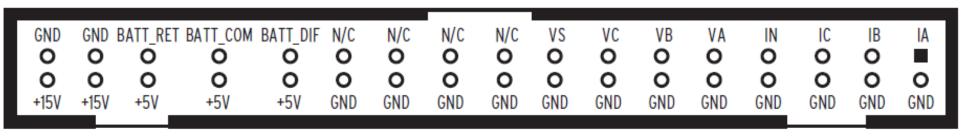


Fig.3.2. Low-Level Test Interface Connector (J2 or J12) [29]

Since the power supply for the relay mainboard is provided through the ribbon cable between J2 and J12, A custom made ribbon with an additional signal output is needed to access the input connector J12. Fig 3.3 shows the custom-made ribbon cable.

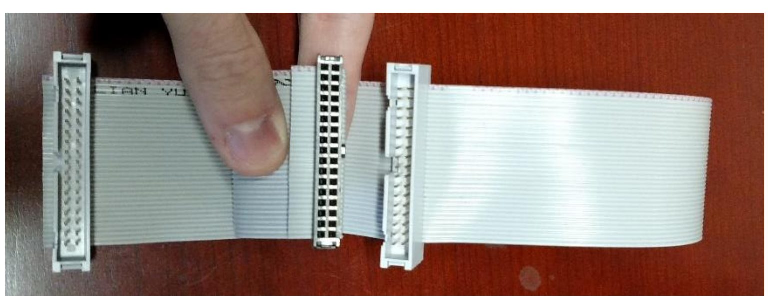


Fig. 3.3. Custom Made Ribbon Cable with Three 34-pin Ribbon Connectors

Table 3.1 shows the output (J2) value of the input module (for a given input value into the relay rear panel). The value of input (J12) is the same as output (J2). The scale factor is a constant number. The processing module input (J12) has a maximum 9 V p-p voltage damage threshold.

Table 3.1. Resultant Scale Factors for Input Module[29]

Input Channels (Relay Rear Panel)	Input Channel Nominal Rating	Input Value	Corresponding J2 Output Value	Scale Factor (Input/Output)
IA, IB, IC, IN	1 A	1 A	45.6 mV	21.92 A/V
IA, IB, IC, IN	5A	5 A	45.2 mV	110.60 A/V
IN	0.2 A	200 mA	45.3 mV	4411.76 mA/V[a]
IN	0.05 A	50 mA	11.3 mV	4411.76 mA/V[a]
VA, VB, VC, VS	300 V	67 V_{LN}	299.1 mV	223.97 V/V

Optical isolation output in two RTDS racks are used to interface with the low-level interface connection of the relays to avoid incompatibility issues between RTDS and digital relays as well as improve the accuracy of the small ac input signal.

III. Test and Result

Fig 3.4 shows the testbed diagram for pilot protection test via wireless communication.

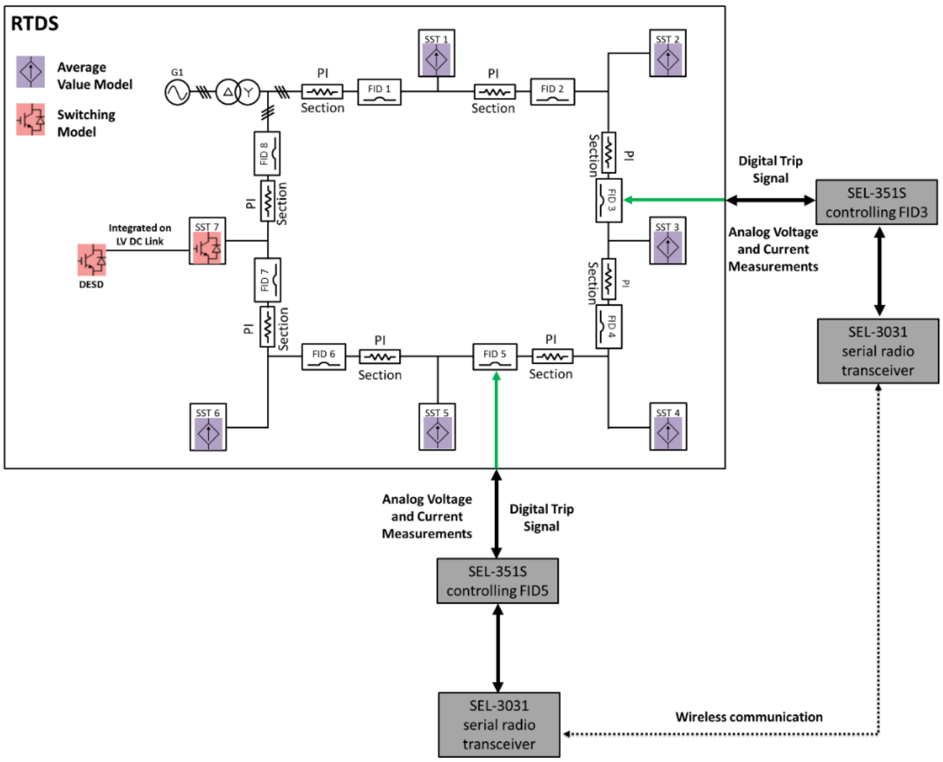


Fig 3.4. FSU-CAPS HIL Testbed Diagram for ASU Protection Hardware Testing

Pilot directional algorithm is used as the protection scheme for the above loop matching the hardware time delays. However, the operation of FID 3 and FID 5 is coordinated with digital relays and radios such that their operation is dependent upon the communication delay between FID 3 and FID 5. This ensures that they won't operate for a fault in any other section of the foundation of the protection algorithm is to detect the fault location (directionality property) using positive sequence impedance. Because negative sequence and zero sequence components are negligible (much less) during a three-phase to ground fault and only positive sequence currents flow in the system. In addition, the entire voltage of the loop momentarily goes to zero during a three-phase fault (bolted ground fault) and the relay has no input voltage to operate. Relay uses memory voltage to detect three phase faults. Memory voltage is the momentary voltage which the relay stores before the voltage of all phases goes to zero. Relay uses this memory voltage and positive sequence components (32PF for forward directional faults or 32PR for reverse directional faults) to determine the fault location. the loop.

In FREEDM loop, the current through FID 3 is clockwise and the current through FID 5 is anti-clockwise. Both relays in FID 3 and FID5 are set to detect forward directional faults while block reverse directional faults. The two relays will exchange direction state via commercial serial radio transceiver. The direction comparison trip logic is shown as Table 3.2. If the two signal matches the trip requirement, the digital relay will send trip signal to FID.

Table 3.2. Trip Logic for FID 3 and FID 5

	Fault direction	Fault direction	Fault direction
Relay at FID 3	Forward	Forward	Reverse
Relay at FID 5	Forward	Reverse	Forward
Trip signal	Trip generated	No trip	No trip

Take the three phase to ground fault as an example, the digital relay at the FID 5 side will send the trip signal only when the corresponding radio transceiver receive the signal that the fault direction at FID 3 is a forward fault. The digital relay at the FID 5 side also detects a forward fault, then the trip signal will be sent to FID 5 to cut off the fault current in the protection zone. Fig 3.5 shows relay event report for FID 5, fault current, voltage at FID 5 and trip signal can be seen from Fig 3.5. Fig 3.6 shows the fault current through FID 5 obtained from the RTDS. The curves from RTDS matches the curves from digital relay, except that the trip time obtained from the relay is shorter because there is a small-time delay for RTDS processing and transmitting.

Relays are connected to FID 3 and FID 5. The fault is applied close to FID 3 in the section between FID 3 and FID 5 to simulate the worst condition where the line to neutral voltage near FID 3 plummets to zero during the fault. This test performs 11 types of faults including single line to ground, double line to ground, line to line, three phase to ground (ABC-G) and three phase line faults (ABC-LLL). The faults are applied when the reference phase (the first phase in the fault name, for example, the reference phase of BC-LL fault is phase B) angles reach 0°, 90°, 180°and 270° respectively. Tables 3.3 and 3.4 show the trip time of FID 3 and FID 5 for different fault types and angles, which is helpful to learn the performance of the pilot protection with wireless communication link. For Fig 3.5, the red dotted line shows the relay detects the fault in less than 1 cycle. The green solid line is phase A current, the blue solid line is phase B current, the red solid line is phase C current, the purple solid line is phase A voltage, the yellow solid line is phase B voltage, and the indigo solid line is phase C voltage. For Fig 3.6, the blue solid line is phase A current, the red solid line is phase B current, the black solid line is phase C current.

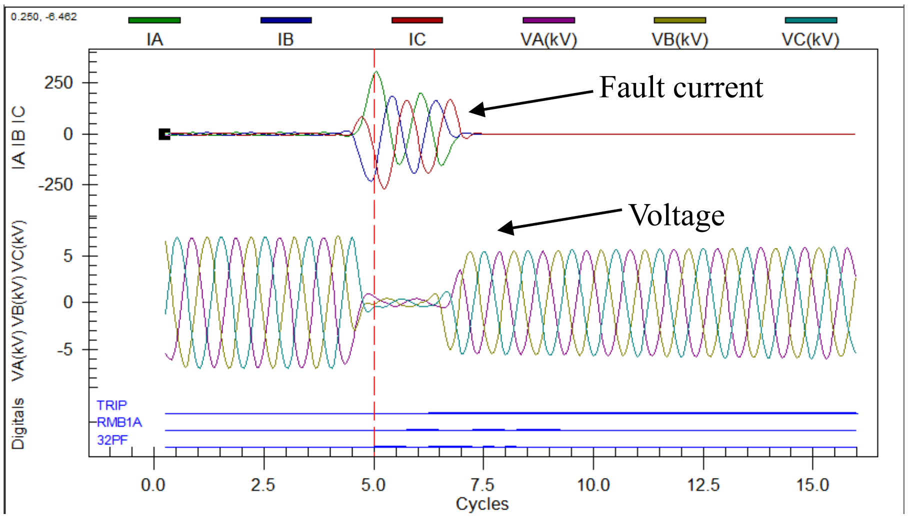


Fig.3.5. Relay Event Report for FID

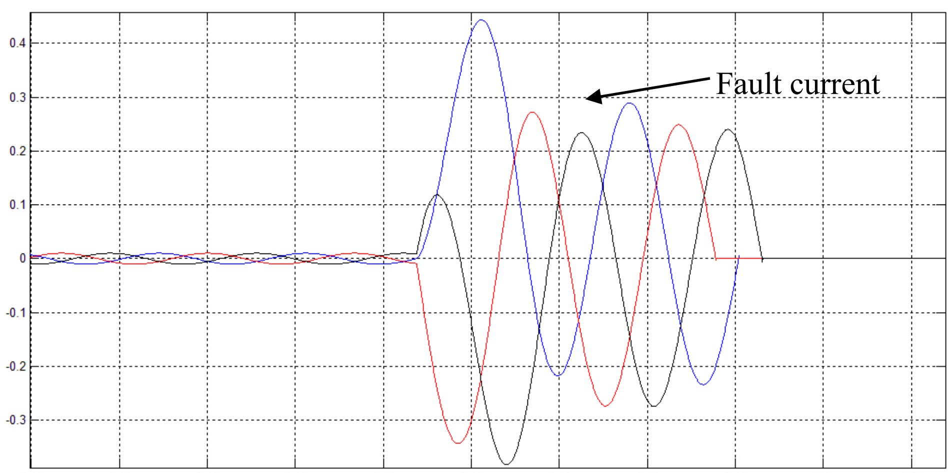


Fig.3.6. Current through FID 5 in RTDS

Table 3.3 FID 3 Trip Time for Different Fault Types and Angles

Fault type	0 degree	90 degree	180 degree	270 degree
SLG-A	28.7ms	33.3ms	27.8ms	26.1ms
SLG-B	27.7ms	25.6ms	28.1ms	26.1ms
SLG-C	30.5ms	28.1ms	28.5ms	29.3ms
AB-G	25.2ms	29.0ms	27.8ms	25.7ms
BC-G	28.0ms	24.8ms	26.9ms	29.5ms
CA-G	23.0ms	30.1ms	25.6ms	29.6ms
ABC-G	32.1ms	28.6ms	32.2ms	28.9ms
AB(LL)	26.1ms	31.7ms	25.9ms	25.2ms
BC(LL)	30.5ms	32.9ms	31.1ms	25.7ms
CA(LL)	25.7ms	29.8ms	26.7ms	25.7ms
ABC-LLL	28.5ms	31.0ms	30.3ms	28.7ms

Table 3.4 FID 5 Trip Time for Different Fault Types and Angles

Fault type	0 degree	90 degree	180 degree	270 degree
SLG-A	25.9ms	27.2ms	25.9ms	28ms
SLG-B	31.3ms	32.1ms	34.4ms	31.2ms
SLG-C	29.0ms	30.9ms	31.4ms	32.2ms
AB-G	24.3ms	29.7ms	24.3ms	31.8ms
BC-G	29.2ms	31.9ms	33.8ms	29.8ms
CA-G	24.3ms	33.0ms	27.5ms	33.8ms
ABC-G	32.1ms	30.7ms	31.4ms	31.3ms
AB(LL)	29.5ms	22.2ms	29.3ms	28.8ms
BC(LL)	30.5ms	29.3ms	31.2ms	36.4ms
CA(LL)	28.7ms	26.1ms	25.6ms	27.7ms
ABC-LLL	29.6ms	27.5ms	29.1ms	30.0ms

B. Test 2

Test 2 expands test 1 to multiple relays coordination and test the behavior of multiple relays. Restricted to the limitation of the available digital relays, a virtual relay is built at FID5 in RTDS to coordinate with two physical relays placed at FID2 and FID3. In order to achieve this, assumption is made based on test 1 that the response time together with the communication delay for the digital relay is 0.25 cycles. Thus, FID 5 will operate 0.25 cycles after the FID 3 operate when the same fault as test 1 occurs.

In this case, an additional direction comparison trip logic between FID 2 and FID 3 is added to the existing trip logic for FID 3 and FID 5 shown in Table 3.5 shows the additional trip logic for FID 2 and FID 3.

Table 3.5. Trip Logic for FID 2 and FID 3

	Fault direction	Fault direction	Fault direction
Relay at FID 2	Forward	Forward	Reverse
Relay at FID 3	Forward	Reverse	Forward
Trip signal	No trip	Trip generated	No trip

According to Table 3.5, FID 2 will not trip because it is a forward fault for FID 2, and also a forward fault for FID 3, the two corresponding radio transceivers receive mismatch signals so that no trip signals generated by the digital relay. Take the three phase to ground fault as example, Fig 3.7 and Fig 3.8 show the event report obtained from digital relay for FID 2 and FID 3 respectively. Fig 3.9 shows the current through FID 5 obtained from RTDS. These plots prove that only FID 3 and FID 5 operate and FID 2 will not operate when a fault occurs between FID 3 and FID 5. The figures also prove that more than two radio transceivers can build reliable and stable communication link without mixing up the directional information.

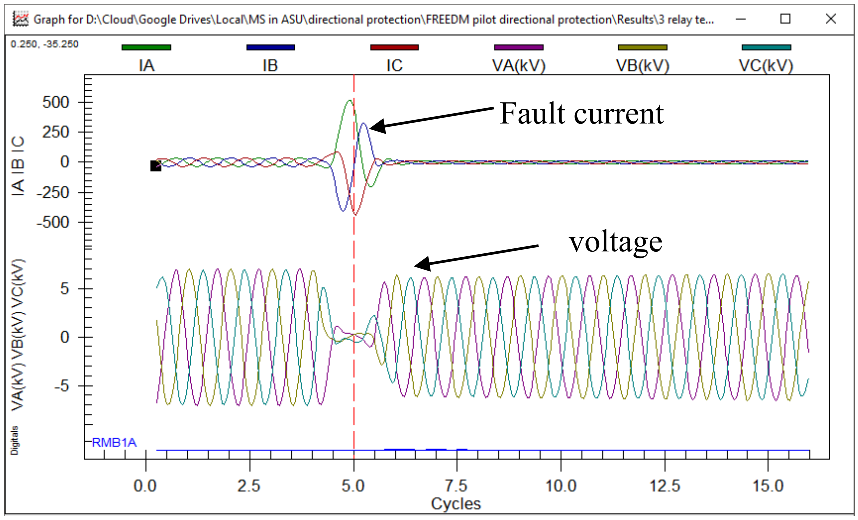


Fig. 3.7. Relay Event Report for FID 2

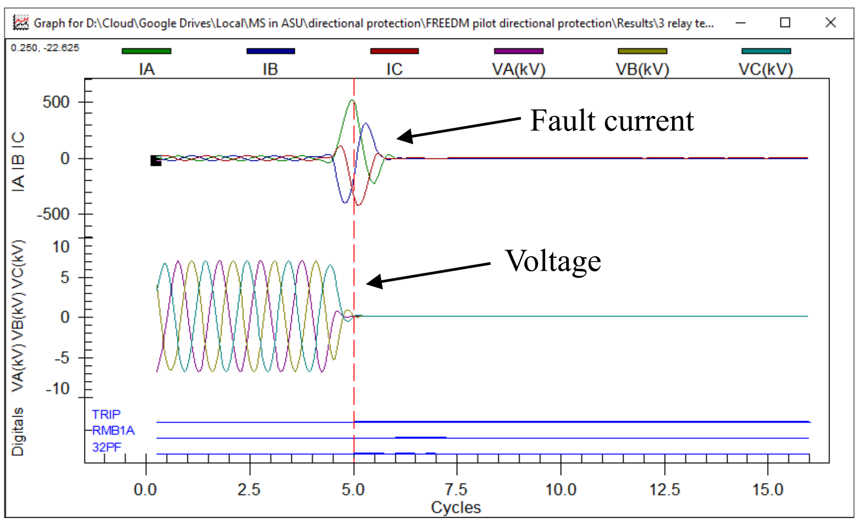


Fig 3.8. Relay Event Report for FID 3

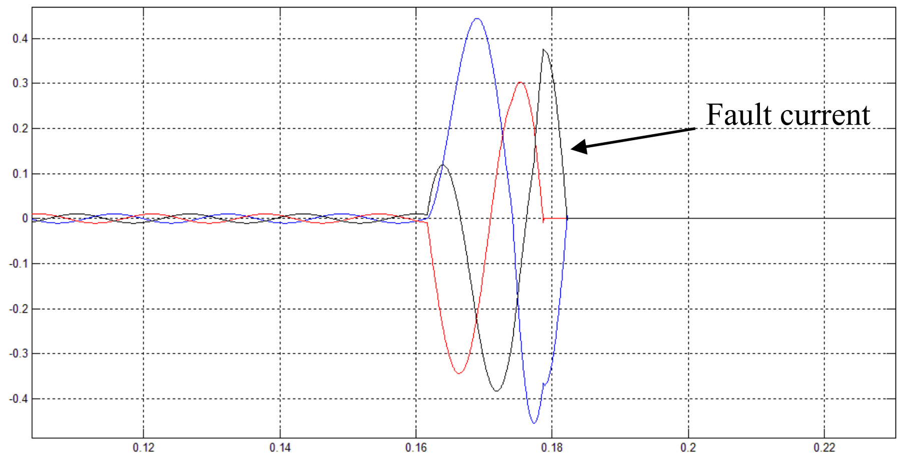


Fig. 3.9. Current through FID 5 in RTDS

IV. Conclusion

From test 1, the operating time taken by FIDs is between 1.38 cycles (23.0 ms) to 2.03 cycles (36.4 ms). The typical latency of radio link working at 19200 bps is 5.6 ms. The approximate processing delay is around 22.4 ms, which matches the minimum operating time for FIDs. The operating delay for wireless communication is acceptable comparing with the operating time of fiber optics, which is between 1.25 to 2.37 cycles according to the test results prepared in 2013

Test 2 verified the feasibility and reliability of pilot protection via wireless communication for multi-relay system. The relays can communicate with up to 8 relays with usage of radio 1ink and conveniently provide primary zone protection in complicated substations with organized communication paths.

In conclusion, the pilot directional protection can provide feasible and reliable protect for FREEDM loop system within an acceptable operation delay. Further studies are desired on multiple physical relay coordination and communication security.

CHAPTER IV

PILOT BACK-UP PROTECTION BASED ON WIRELESS COMMUNICATION

I. Introduction of The Back-Up Protetcion

The pilot directional main protection system is developed to detect the existence and location of faults at very high speeds. When the main protection does not work, the back-up protection must provide support and detect the fault. A simplified wireless communication scheme is presented in this chapter for back-up protection which could be helpful for detecting faults because the power flow is bidirectional in loop system. And the speed of the wireless communication also meets the requirement for the back-up protection. The sequence components are used to determine the fault location. A radial system using commercial relays has been designed to validate the back-up protection scheme.

II. System Setup of Pilot Back-Up Protection

A remote back-up protection scheme is developed for the FREEDM loop which could be used to detect all type of fault in the system when the main protection does not work. Fig.4.1 shows the remote back-up protection diagram in the FREEDM loop system, the FID (fault isolation device), which is an electronic circuit breaker in the FREEDM loop, can isolate the fault. Each FID is equipped with a digital relay to collect line information and send operation signals, and the SSTs are used to replace the conventional 60Hz power transformer with power electronic power processing package. The main protection has been developed in previous section, when the main protection does not work, the digital relay using the back-up protection scheme will detect the fault and send trip signal to FID to isolate the fault. According to the different types of the fault, the back-up protection can also be divided into two parts, one is the detection of unsymmetrical fault the other one is the detection of symmetrical fault.

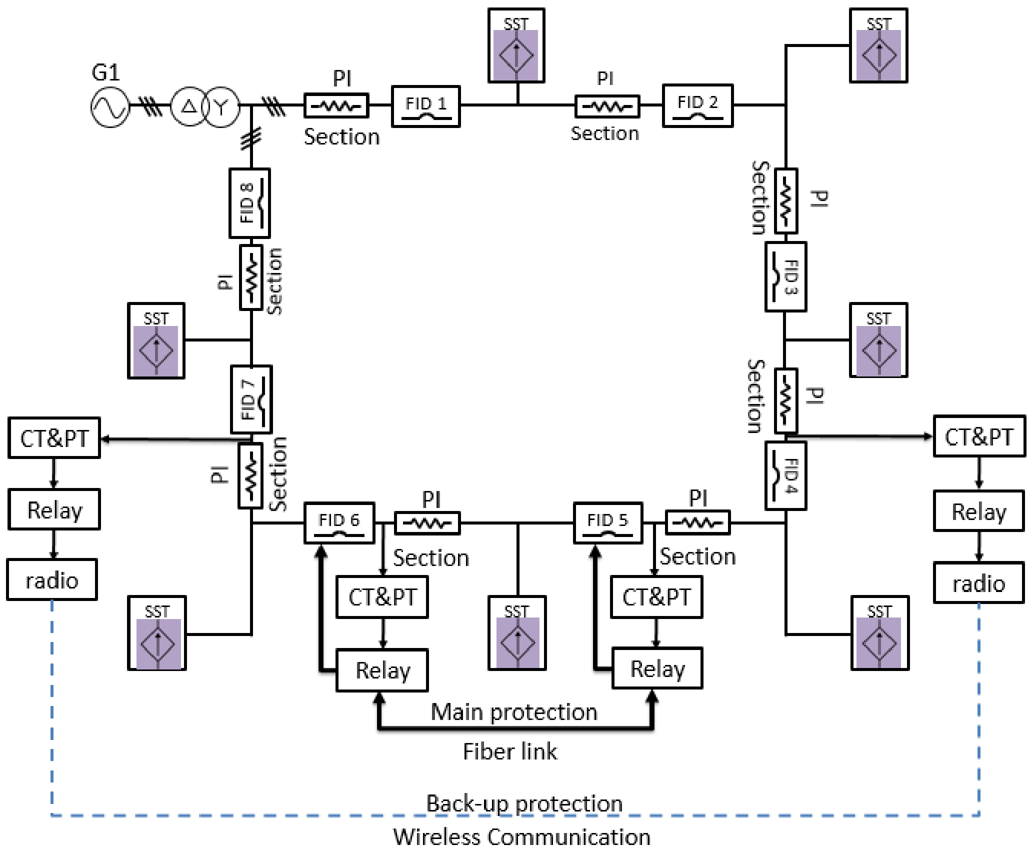


Fig 4.1. Remote Back-up Protection Diagram

III. Implementation of Back-Up Protection in SIMULINK

The back-up protection scheme is simulated in the Simulink from the MATLAB software. The simulation is also divided into two parts, one is for symmetrical fault and the other is for asymmetrical fault.

A. Detection of Unsymmetrical Faults

A radial system is simulated to validate the back-up protection scheme. The voltage and current can be measured by current transformer and potential transformer, by analyzing the data, the negative sequence method will generate +1 or -1 depending on the fault location. Fig 4.2 shows the '3 phase sequence analyzer' block which is added to get the sequence components of voltages and current.

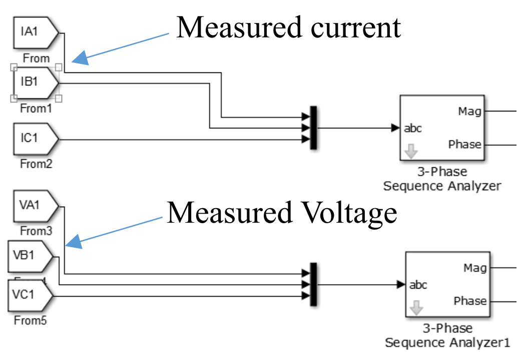


Fig 4.2. Three Phase Sequence Analyzer Block

After getting the negative sequence components, the negative impedance can be obtained from (3-2). If the calculated Z2 is less than forward threshold impedance Z2F, the directional element generates +1, but if the calculated impedance is greater than the reverse threshold impedance Z2R, it generates an output of -1. During normal operation, the scheme output remains zero.

B. Detection of Symmetrical Faults

The three-phase sequence analyzer is also used to get the positive sequence components, and they are delayed by one cycle and being continuously compared with the present components of positive sequence voltage and current.

The positive sequence scheme is dependent on the overcurrent element compared with the negative sequence scheme because the positive sequence components also exist in the situation that no fault occurs in the system. The overcurrent element is added to detect whether there is a fault in the system, when all three phase current are higher than the threshold current, then the back-up protection will choose the positive sequence component to get the fault direction. Fig 4.3 shows the overcurrent element that decides the back-up protection scheme.

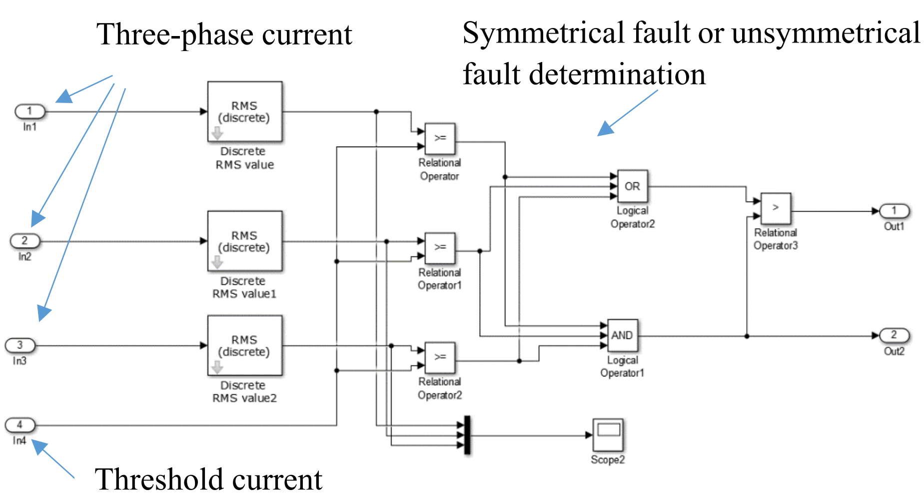


Fig 4.3 The Determination of Protection Scheme Based Overcurrent Element

The phase angle difference between the positive voltage and positive current is calculated, the positive method will generate +1 when it is a forward direction fault and -1 when it is a reverse direction fault.

C. Remote Back-Up Protection

After combining the two protection schemes together, the time-delay component is added to coordinate with the main protection. Fig 4.4 shows the time-delay component, based on that the over-current back-up protection coordination time is larger than 2 cycles if the main protection does not work, the coordination time of the remote back-up protection is set as 5 cycles.

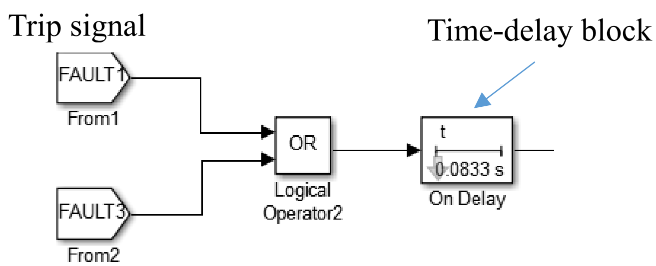


Fig 4.4. The Time-delay Component for The Back-up Protection

Fig 4.5 shows the radial system in simulation, the remote back-up protection system uses two relays to get the fault direction and send trip signal to the circuit breaker to isolate the fault. Table 4.1 shows the trip logic for the simulation.

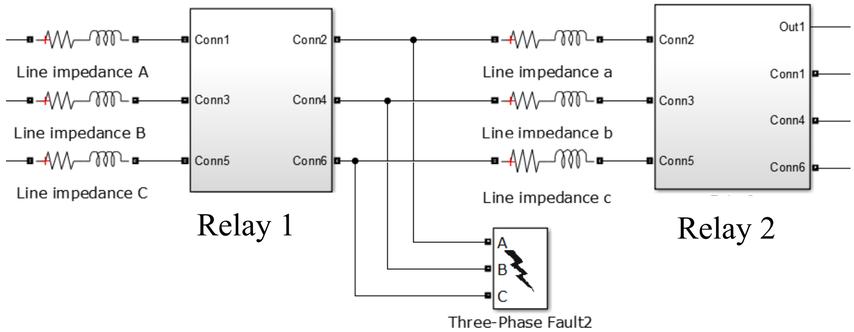


Fig 4.5. The Radial System for The Back-up Protection in SIMULINK

Table 4.1. Trip Logic for The Simulation

	Fault direction	Fault direction	Fault direction	Fault direction
Relay 1	Forward	Forward	Reverse	Reverse
Relay 2	Reverse	Forward	Forward	Reverse
Trip signal	Trip generated	No trip	No trip	No trip

D. Simulation Result

Fig 4.6 shows the simulation result of three phase current in the system from three types of fault, single phase to ground fault, phase to phase fault, and three phase to ground fault. The red solid line is phase A current, the blue solid line is phase B current, the green solid line is phase C current.

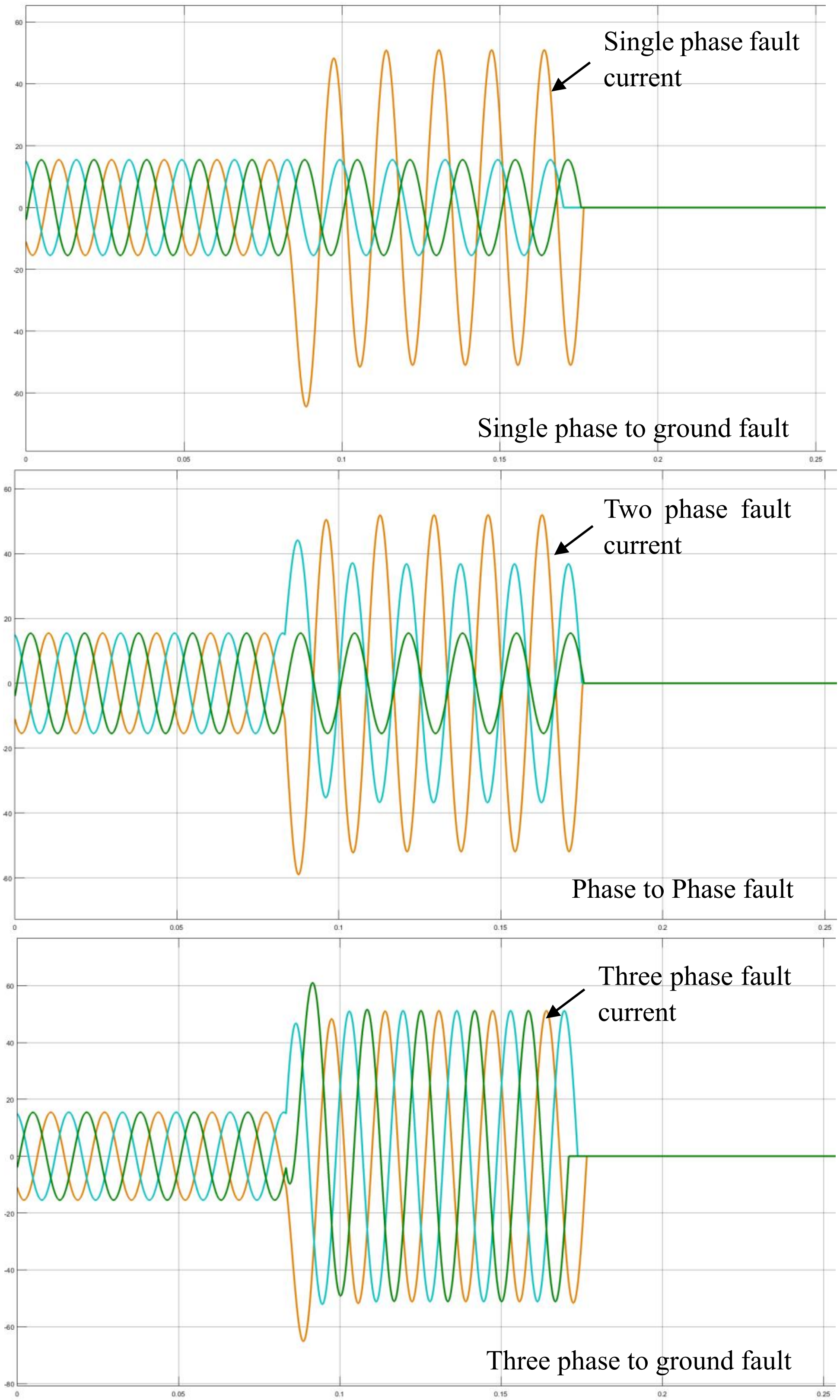


Fig 4.6. Simulation Result from Three Types of Fault

The trip time is 5.5 cycles with back-up protection, since there is 5 cycle time-delay, the latency of the two relays determine the fault direction and communication is 0.5 cycle, which is negligible. When it comes to the practical situation, the latency that the relay determines the fault direction and the delay between the wireless communication is larger than half a cycle, it is about 5 cycle, so the total trip time is expected at about 8 cycles.

IV. Hardware Implementation

A Test bed has been built to validate the protection scheme, Fig 4.7 shows the laboratory setup of back-up protection with digital relays.

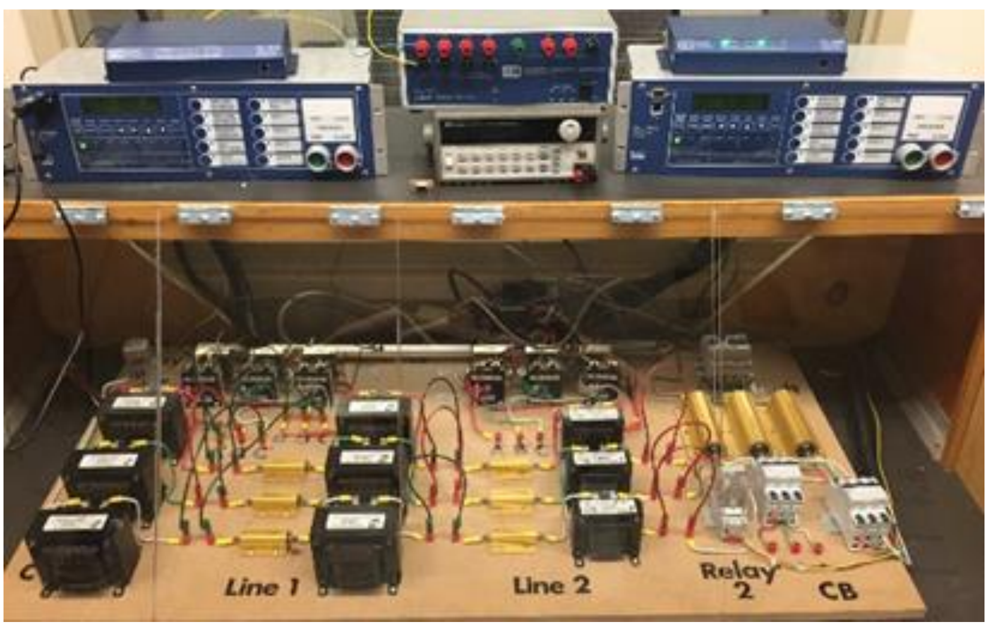


Fig 4.7. Laboratory Setup of Power System Protection with Digital Relays

Normally, the main protection uses fiber optic to build communication link to get the high-speed operation, for back-up protection, the delay of the wireless communication is acceptable. Commercial relay and radio link is used to implement the back-up protection algorithm. The radio link can simultaneously communicate with up to three independent ports and protocols via point-to-point radio operation.

For unsymmetrical fault, Fig 4.8 shows two fault events during the single phase to ground fault, one shows the three-phase current when the main protection works and the other one shows the three-phase current when the back-up protection works. The green solid line is phase A current, the blue solid line is phase B current, the red solid line is phase C current.

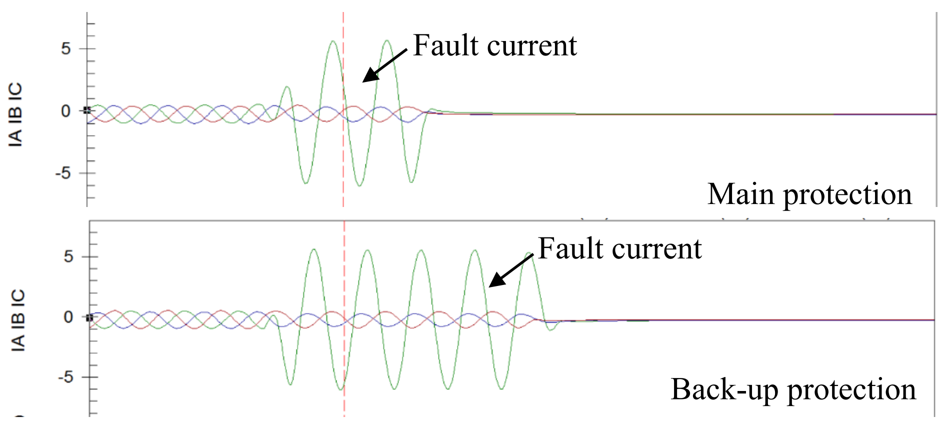


Fig 4.8. Fault Event of A Single Line to Ground Fault with Main and Back-up Protection

For symmetrical fault, Fig 4.9 shows two fault events during the three phase to ground fault, one is with main protection and the other one is with back-up protection.

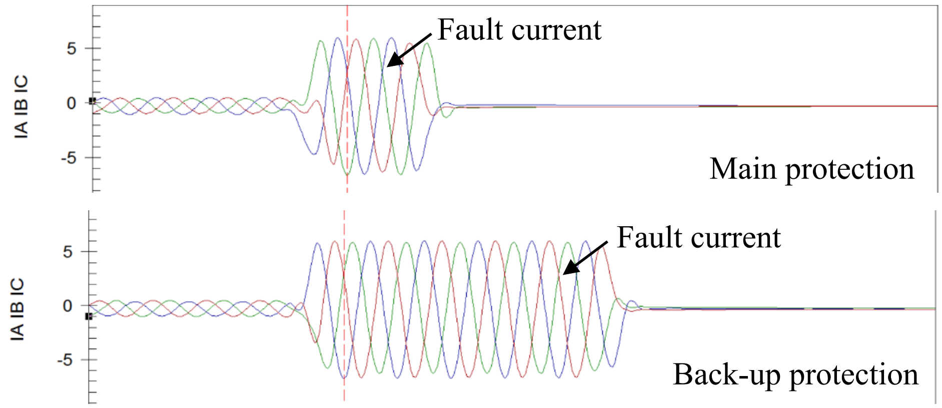


Fig 4.9. Fault Event of Three Phase to Ground Fault with Main and Back-up Protection

V. Conclusion

The pilot back-up protection scheme with wireless communication has been successfully demonstrated in this chapter. The scheme effectively detects both symmetrical and unsymmetrical fault. The wireless communication shows a better economical efficiency compared with the fiber transmitting format over long distance. The wireless mode of communication is effective for sharing the information between the two relay. The delay time can be adjusted to meet the requirement for the coordination with the main protection. This section presents an effective back-up protection to the loop system.

CHAPTER V

ECONOMICAL PROTOTYPE OF PILOT DIRECTIONAL PROTECTION SYSTEM BASED ON MATLAB

I. Introduction of The MATLAB Based Protection System

The pilot directional protection scheme is developed to detect the existence and location of faults at very high speeds. In order to apply the scheme on the practical situation, a protection system is built using laptops and data acquisition devices to work as digital relays. Data acquisition (DAQ) is the process of measuring an electrical phenomenon such as voltage, current with a computer. A DAQ system consists of sensors, measurement hardware, and a computer with programmable software. The data acquisition device can directly transmit real-time line data into the laptop, the laptop uses MATLAB to analyze the data, and generates the fault direction signal. A simplified wireless communication scheme based on User Datagram Protocol (UDP) is presented later for protection which could be helpful for detecting faults because the power flow is bidirectional in loop system, and the speed of the wireless communication also meets the requirement for the protection. The sequence components are used to determine the fault location.

Fig 5.1 shows the pilot differential protection diagram in the FREEDM loop system, the FID (fault isolation device), which is an electronic circuit breaker in the FREEDM loop that can isolate the fault. The analog to digital signal converter (ADC) can obtain analog signal from the potential transformer and current transformer, and then translate into digital signal to the laptop. The laptop will run a MATLAB code to determine the fault current direction, by communicating wirelessly with the adjacent laptop, the trip signal will be generated and the laptop will send trip signal to FID to isolate the fault. According to the different types of the fault, the protection scheme is divided into two parts, one is the detection of unsymmetrical fault the other one is the detection of symmetrical fault.

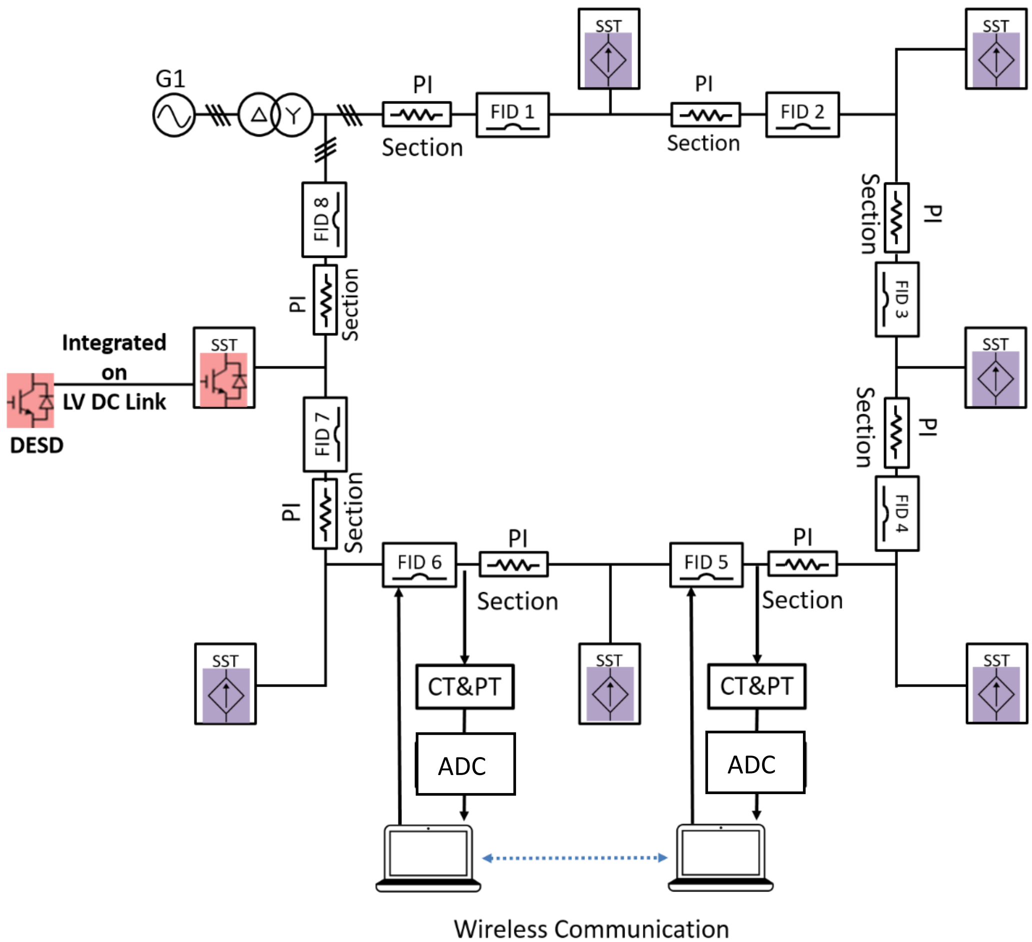


Fig 5.1. Diagram of The Protection System for FREEDM Loop

II. System Setup of Protection System

A. Test Bed Setup

The connection diagram of the physical platform is shown in Fig 5.2. The one-line diagram of the whole system is shown in Fig 5.3.

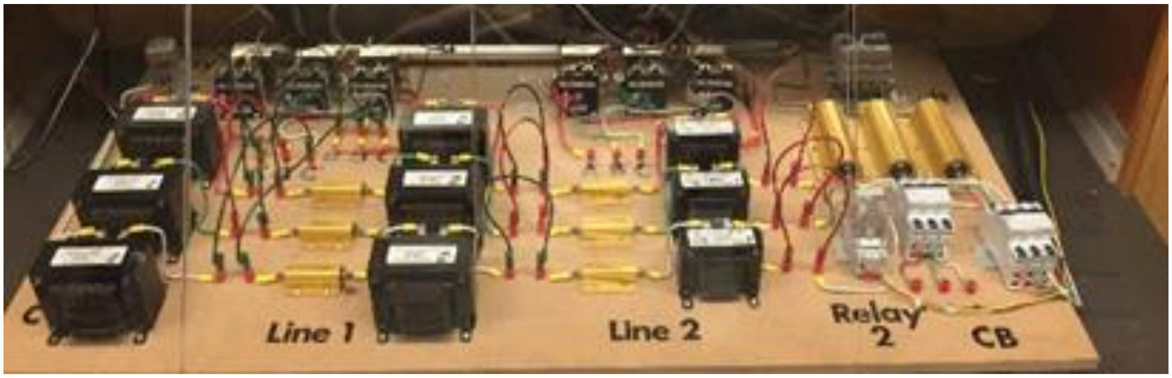


Fig 5.2. Laboratory Setup of System

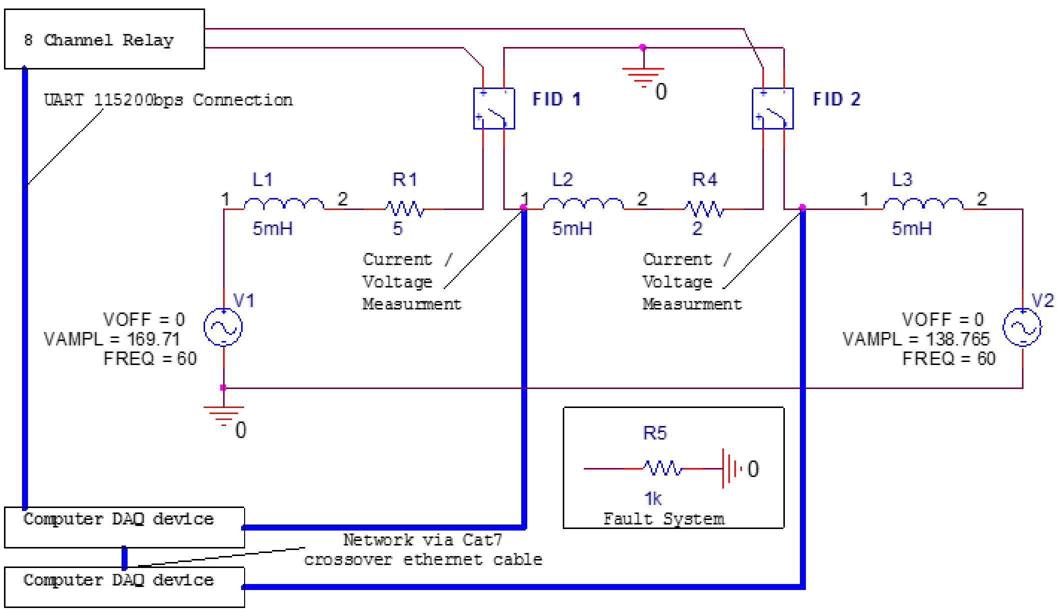


Fig 5.3. One-line Diagram for The Test Bed and The Protection System

B. Data Acquisition Setup

The analog to digital signal converter used in the power system can accept the analog alternate voltage signal which range is from -10 V to +10 V. Therefore, the current transformer and potential transformer need additional circuit to get the expected voltage signals.

1) Current Measurement:

A resistance is connected in series with the secondary side of the current transformer, one end of the resistance is connected to the ground, therefore, the current can be measured by determining the voltage drop on the resistance, the fault current measured by the current transformer is about 5 A, so the voltage drop on the resistance is 5V. Fig 5.4 shows the connection diagram.

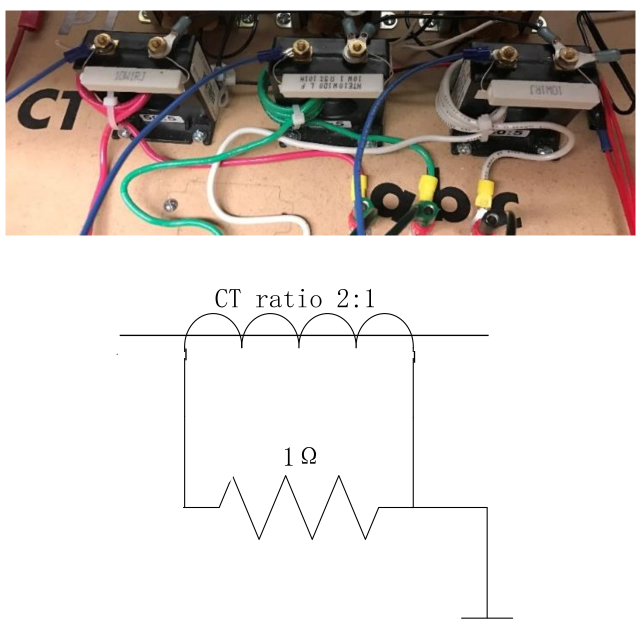


Fig 5.4. The Connection Diagram for The Current Measurement

2) Voltage Measurement:

Since the data acquisition device can only accept voltage between +10 V and -10 V, a voltage divide circuit is designed get lower voltage signal, Fig 5.5 shows the connection diagram for the voltage measurement.

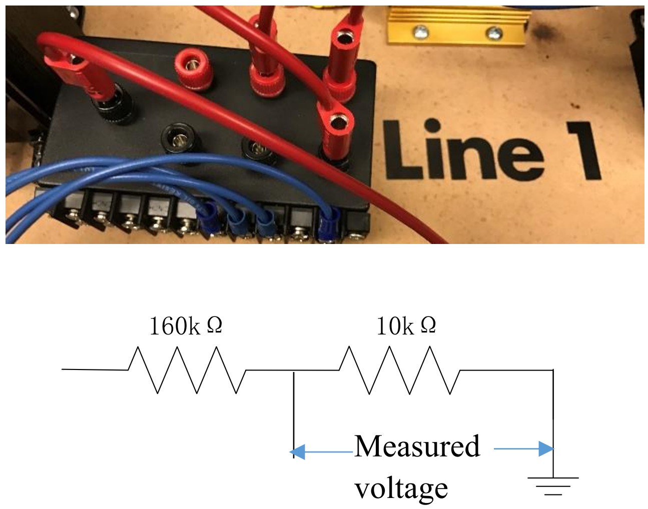


Fig 5.5. The Connection Diagram for The Voltage Measurement

C. MATLAB Setup

The Fast Fourier Transform is used to get the sequence value at fundamental frequency, the zero sequence, positive sequence and negative sequence elements can be calculated by using the fundamental voltage and current values. The fast Fourier transform (FFT) is a discrete Fourier transform algorithm which reduces the number of computations needed for N points from $2N^2$ to $2N\log_2 N$, where $\log_2$ is the base-2 logarithm. Fast Fourier transform algorithms generally fall into two classes: decimation in time, and decimation in frequency.

The FFT algorithm first rearranges the input elements in bit-reversed order, then builds the output transform (decimation in time). The basic idea is to break up a transform of length N into two transforms of length N/2 using the equation below[30]

$$\sum_{n=0}^{N-1} a_n e^{-\frac{2\pi i n k}{N}} = \sum_{n=0}^{\frac{N}{2}-1} a_{2n} e^{-\frac{2\pi i (2n) k}{N}} + \sum_{n=0}^{\frac{N}{2}-1} a_{2n+1} e^{-\frac{2\pi i (2n+1) k}{N}}$$

$$= \sum_{n=0}^{\frac{N}{2}-1} a_n^{even} e^{-\frac{2\pi i n k}{N/2}} + e^{-2\pi i k/N} \sum_{n=0}^{\frac{N}{2}-1} a_n^{odd} e^{-\frac{2\pi i n k}{N/2}} \quad (6\text{-}1)$$

The type of the fault is determined through the rms values of the three-phase current. If all the measured three phase currents are higher than the threshold value, the fault will be defined as the symmetrical fault, and the positive sequence method is applied. If one phase or two phase current is higher than the threshold value, the fault will be defined as the unsymmetrical fault, the negative sequence method is applied. The fault direction will be given to the communication channel to determine whether the fault is in the protection zone. Fig 5.6 shows the flow diagram of the pilot directional protection algorithm.

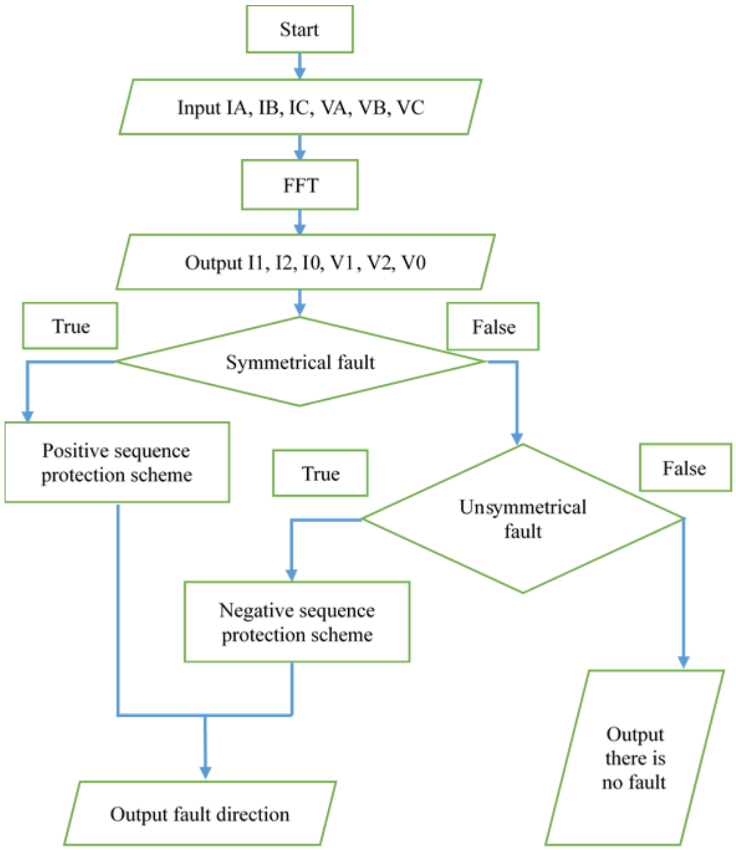
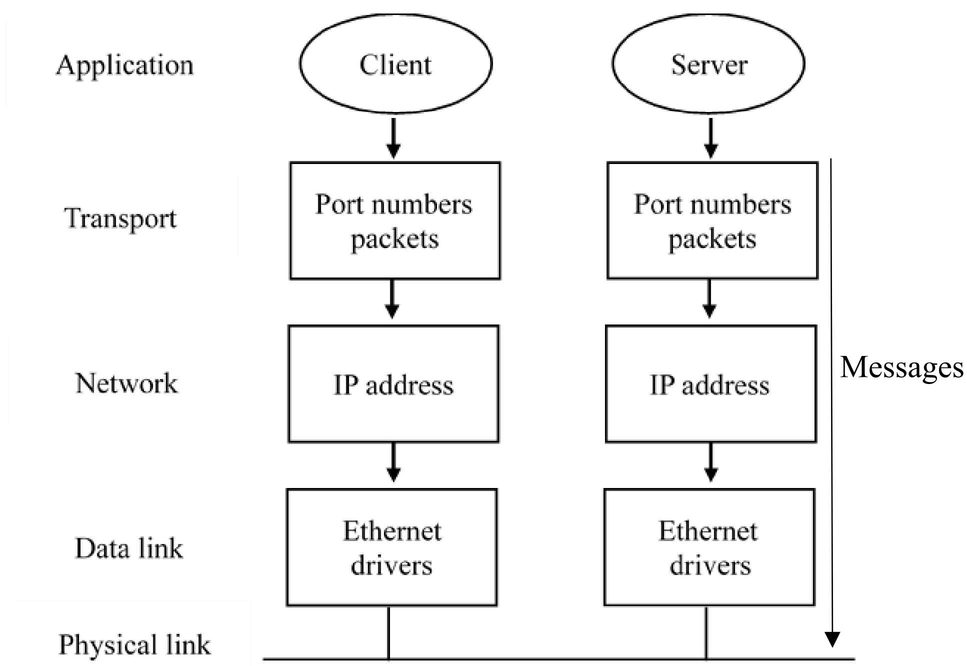


Fig 5.6. The Flow Diagram of The Pilot Directional Protection Algorithm

D. UDP Wireless Communication

The User Datagram Protocol (UDP) is a transport layer protocol defined for use with the Internet Protocol (IP) network layer. The service provided by UDP is a simple internet communication protocol, the protocol needs no hand shake on defining the message which makes the transmitting speed very fast. UDP provides a minimal, best-effort, message-passing transport to applications. [31]

Generally, the source port number is set to a unique number that they choose themselves - usually based on the program that started the connection. Since this number is returned by the server in responses, this lets the sender know which "conversation" incoming packets are to be sent to. The destination port of packets sent by the client is usually set to one of the specific ports. A server process (program), listens for UDP packets received with a well-known port number and tells its local UDP layer to send packets matching this destination port number to the server program. It determines which client these packets come from by examining the received IP source address and the received unique UDP source port number. Any responses which the server needs to send to back to a client are sent with the source port number of the server and the destination port selected by the client. Fig 5.7 shows the diagram of the UDP protocol



(Internet cable or wireless network)

Fig 5.7. UDP Protocol Diagram

E. Trip Logic

Once the fault lies in the protection zone, the fault current direction determined by the two laptops will be opposite, the trip signal will be generated and sent to the circuit breaker. If the fault happens out of the protection zone, the fault current direction determined by the two laptops will be the same. Table 5.1 shows the trip logic for the protection system.

Table 5.1. Trip Logic for The System

	Fault direction	Fault direction	Fault direction	Fault direction
Relay 1	Forward	Forward	Reverse	Reverse
Relay 2	Reverse	Forward	Forward	Reverse
Trip signal	Trip generated	No trip	No trip	No trip

F. Trip Signal Setup

The fault current direction signal generated by one laptop needs to be transmitted to the other laptop through UDP protocol, according to Table 5.1, the trip signal will be generated and sent to the fault interruption devices. The fault interruption devices are magnetic circuit breaker on the testbed triggered by a serial interface within MATLAB. This allows the correct fault interruption device to open and isolate a certain part of the circuit.

III. Test Result

Fig 5.8 shows waveform of the three-phase current under normal situation, the spike on the waveform is the noise which will be filtered by the FFT. The red solid line is phase A current, the blue solid line is phase B current, the yellow solid line is phase C current.

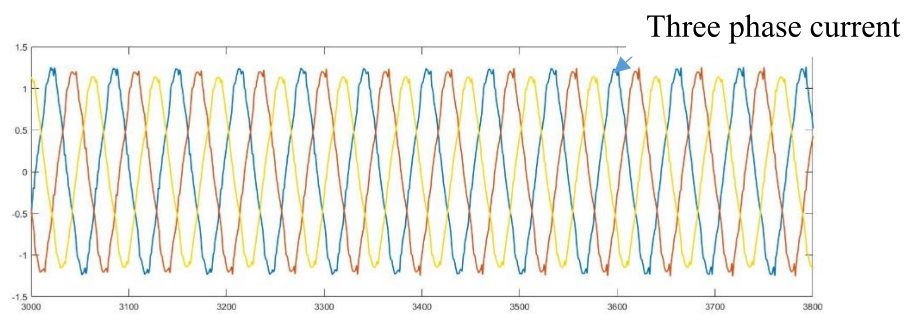


Fig 5.8. Three Phase Current under Normal Situation

Fig 5.9 shows the waveform of the three-phase current when there is a single phase to ground fault that happens out of the protection zone, there is no trip signal generated by the laptop.

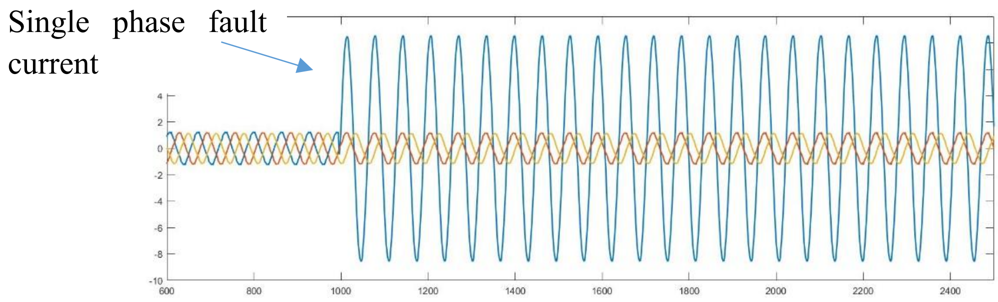


Fig 5.9. Three Phase Current under Single Phase to Ground Fault (out of protection zone)

Fig 5.10 shows the waveform of the three-phase current when there is a single phase to ground fault that happens inside of the protection zone, the trip time is 15 cycles because the data acquisition device takes about 10 cycles to get the line data and convert the analog signal to digital signal. The actual time from the laptop analyze the data to send trip signal is 4 cycles.

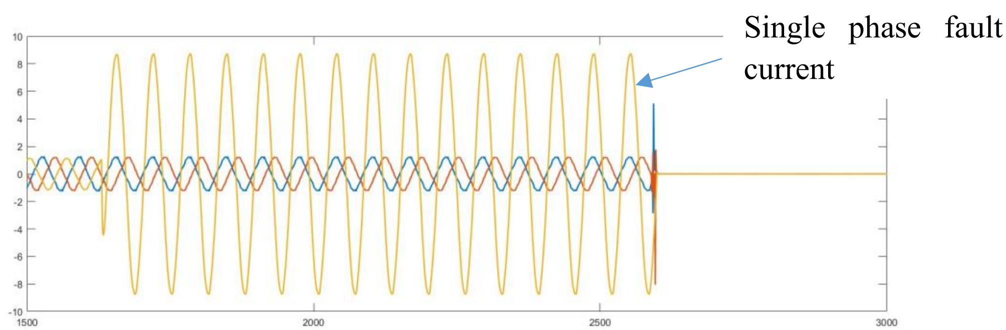


Fig 5.10. Three Phase Current under Single Phase to Ground Fault (inside of protection zone)

IV. System Improvement

A hardware protection system is designed to implement the pilot directional protection scheme which can reduce the high latency of processing the analog signals. The system consists of analog to digital converter unit, a digital signal processing (DSP) module and radio link to build wireless communication. Fig 5.11 shows the diagram of the whole system.

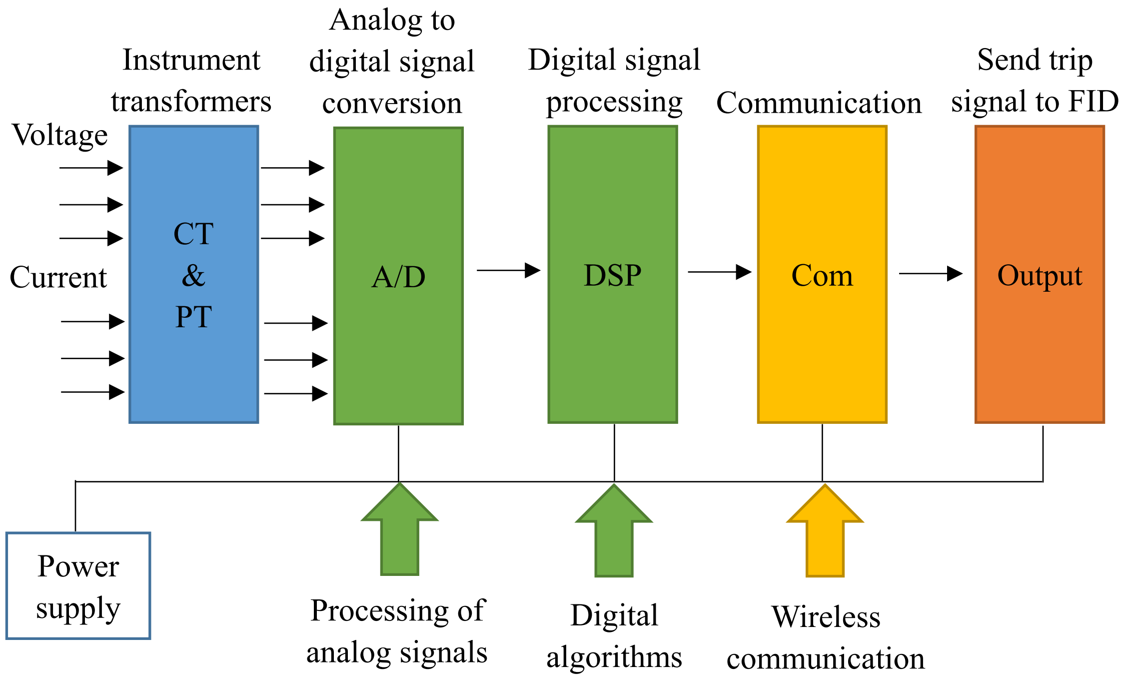


Fig.5.11 The Diagram of The Pilot Directional Protection Hardware System

A. Analog to Digital Converter (A/D) Unit:

The voltages and currents obtained from the power system are first obtained and transferred into analog voltage signals by high speed data capture platform (TSW1400EVM). These analog signals are digitized by passing them through the analog to digital (A/D) converter unit of TMS320F28335 kit, the ADC module consists 16 12-bit pipelined analog-to-digital converter channel and can process 12.5 million samples in a second. Fig 5.12 shows the data capture platform, and Fig 5.13 shows the ADC unit. Since the digital signal processor needs three phase voltage and three phase current simultaneously, the A/D unit must finish the conversion at the same time, so the simultaneous sampling mode is used to convert 6 analog channels of analog voltage signals.

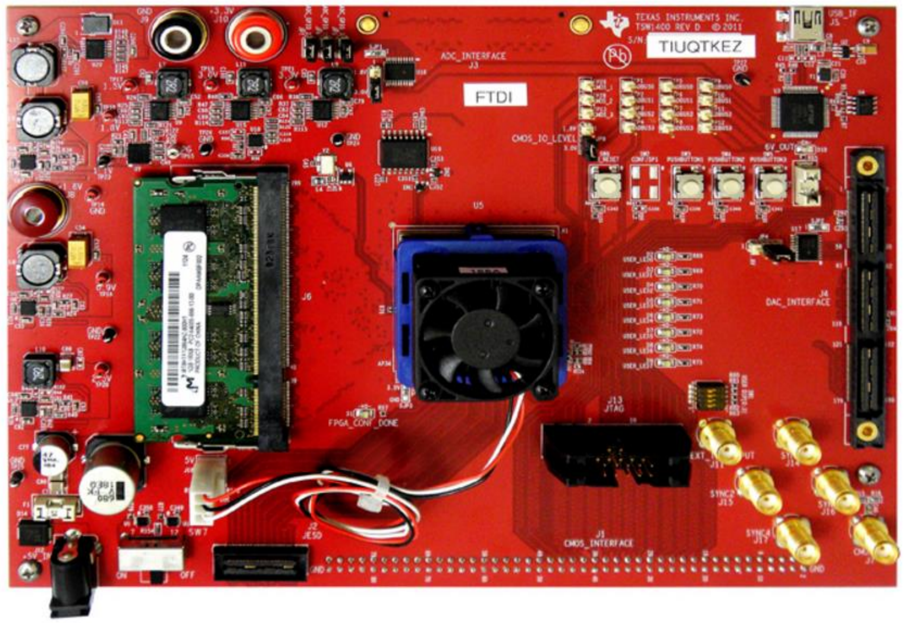


Fig 5.12 The High-speed Data Capture Platform TSW1400EVM [35]

Fig 5.13 The ADC Module with TMS320F28335 Kit

B. Digital Signal Processor:

The protection scheme is coded in C language and linear assembly language. These programs were loaded and executed on a microprocessor. The DSP module, TMS320F28335, is used in the system to identify fault direction. First, the data transferred by the ADC unit are processed by the Fast Fourier Transform to get the fundamental three-phase voltage and current phasor and amplitude. And then these values are used to calculate the sequence components for the negative sequence method and positive sequence method. By comparing with the threshold values, the type of the fault is determined whether it is symmetrical fault or unsymmetrical fault. The DSP will output digital “1” or “0” for the fault direction information.

C. Wireless Radio Link:

The DSP is loaded with the algorithm to determine the fault direction, and sends the information to the wireless radio link, the CC1120 based-device is a fully integrated single-chip radio transceiver designed for high performance at very low-power and low-voltage operation in cost-effective wireless systems. The tool for 868 to 915 MHz uses the CC1120DK chip, it can communicate over 60 miles possible, and 1 mile range in dense urban environment with 868MHz. Fig 5.13 shows the wireless communication tool.

Fig 5.13 Sub-1GHz Wireless Long Range Communication Tool with CC1120 [35]

D. Interface With Fault Isolation Device:

Once the DSP has a trip signal, the TMS320F28335 board can transfer the digital signal into analog 5V signal which can be transmitted directly to the mechanical switch of the fault isolation device (FID).

IV. Conclusion

This chapter demonstrates a pilot differential protection system, which can effectively detect both symmetrical and unsymmetrical fault. The wireless mode of communication is effective for sharing the information between the adjacent relay. The use of wireless communication for transmitting fault direction signals has been successfully demonstrated in this chapter. The whole system costs 90% less budget compared with the commercial relays, which is much more economical. The software platform used in this chapter is widely used and easy to access, which is convenient for the research goal. And the system is easy to co-operate with other devices in the FREEDM loop. The trip time needs to be reduced by improving the measurement method, a protection system is proposed to reduce the data processing time, the system can send trip signals directly to the fault isolation device and have a stable, long range wireless communication, the cost for the system is one-third of the commercial products.

CHAPTER VII

CONCLUSION AND FUTURE WORK

I. Conclusion:

This thesis presents the design and validation of the protection system for the Future Renewable Electric Energy Delivery and Management (FREEDM) system. The pilot directional protection scheme with wireless communication is discussed in this thesis.

1. A commercial product based protection system with wireless communication is used in this thesis. Directional overcurrent based relays detect and sectionalize the faulty section from the healthy system. The wireless communication is found to have comparable speed and selectivity. A hardware implementation is built under the assistance of ASU student Qiushi Wang at the ASU power laboratory.

2. The pilot directional protection with wireless communication is validated in the real time digital simulator (RTDS) system in CAPS, Florida. The interface between the RTDS and the upper-level panel of the digital relay is successful. The digital relay can detect the fault in less than half a cycle.

3. The research also presents a back-up protection system for the loop system. The wireless communication prevents the use of expensive dedicated fiber transmitting over long distance. The wireless mode of communication is effective for sharing the information between the two relays. The delay time can be adjusted to meet the requirement for the

coordination with the main protection. This part of the research work is published in the 2017 Green Tech Conference Meeting in Denver, 2017. []

4. Due to the high cost of the commercial relay, an economical protection system is presented in the research. The whole system only costs 33% of commercial relays, which is more economically efficient. The software platform in this thesis is widely used and easy to access, which is convenient for the research goal. The system is also easy to co-operate with other devices in the FREEDM loop.

II. Future Work

The following aspects could be added to the research work:

1. The time delay losses via the radio link can be modeled in MATLAB and PSCAD to study the impact on trip signal delay.

2. The development of PMU based secondary protection for the large mesh distribution system.

3. The digital relay operating information can be collected and build communication with DGI

5. DSP devices can be studied to replace the digital relay by analyzing the digital signals of line and send trip signals to the fault isolation device.

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APPENDIX A

MATLAB CODE

```
% Relay 1 setting
% Build connection between DAQ and computer
d=daq.getDevices;
s = daq.createSession('ni');
addAnalogInputChannel(s,'Dev1',0,'Voltage');
addAnalogInputChannel(s,'Dev1',1,'Voltage');
addAnalogInputChannel(s,'Dev1',2,'Voltage');
addAnalogInputChannel(s,'Dev1',3,'Voltage');
addAnalogInputChannel(s,'Dev1',4,'Voltage');
addAnalogInputChannel(s,'Dev1',5,'Voltage');
% Set DAQ scan rate and time
s.Rate =1280;
s.DurationInSeconds = 1/60;
i = 0;
time=200;
aline=10;
D = [];
Z2 = 0;
%Build wireless communication using UDP protocol
udpN = udp('192.168.1.1', 9091, 'LocalPort', 9090);
fopen(udpN);
udpN= udp('10.206.203.219', 9091, 'LocalPort', 9090);
fopen(udpN);
flushinput(udpN);
% Run the main loop
   while(1)
   if fread(udpN)==10;
        fwrite(udpN,12);
%Record the line data
   data = s.startForeground();
   IA=data(:,4);
   IB=data(:,5);
   IC=data(:,6);
   VA=data(:,1);
   VB=data(:,2);
   VC=data(:,3);
%Use fast Fourier transform to get fundamental values
   Ia=fft(IA,64);
   Ib=fft(IB,64);
   Ic=fft(IC,64);
```

```
    Va=fft(VA,64);
    Vb=fft(VB,64);
    Vc=fft(VC,64);
    Mia=(abs(Ia(4)));
    Mib=(abs(Ib(4)));
    Mic=(abs(Ic(4)));
    Mva=(abs(Va(4)));
    Mvb=(abs(Vb(4)));
    Mvc=(abs(Vc(4)));
    Mia=Mia/32;
    Mib=Mib/32;
    Mic=Mic/32;
    Mva=Mva/32;
    Mvb=Mvb/32;
    Mvc=Mvc/32;
    Pia=phase(Ia(4));
    Pib=phase(Ib(4));
    Pic=phase(Ic(4));
    Pva=phase(Va(4));
    Pvb=phase(Vb(4));
    Pvc=phase(Vc(4));
    aa=cos(2*pi/3)+1i*sin(2*pi/3);
% Calculate positive sequence component, negative
sequence component and zero sequence component

I0=((Mia*cos(Pia)+1i*Mia*sin(Pia))+(Mib*cos(Pib)+1i*Mib
*sin(Pib))+(Mic*cos(Pic)+1i*Mic*sin(Pic)))/3;

I1=((Mia*cos(Pia)+1i*Mia*sin(Pia))+aa*(Mib*cos(Pib)+1i*
Mib*sin(Pib))+aa^2*(Mic*cos(Pic)+1i*Mic*sin(Pic)))/3;

I2=((Mia*cos(Pia)+1i*Mia*sin(Pia))+aa^2*(Mib*cos(Pib)+1
i*Mib*sin(Pib))+aa*(Mic*cos(Pic)+1i*Mic*sin(Pic)))/3;

V0=((Mva*cos(Pva)+1i*Mva*sin(Pva))+(Mvb*cos(Pvb)+1i*Mvb
*sin(Pvb))+(Mvc*cos(Pvc)+1i*Mvc*sin(Pvc)))/3;

V1=((Mva*cos(Pva)+1i*Mva*sin(Pva))+aa*(Mvb*cos(Pvb)+1i*
Mvb*sin(Pvb))+aa^2*(Mvc*cos(Pvc)+1i*Mvc*sin(Pvc)))/3;
```

```
V2=((Mva*cos(Pva)+1i*Mva*sin(Pva))+aa^2*(Mvb*cos(Pvb)+1
i*Mvb*sin(Pvb))+aa*(Mvc*cos(Pvc)+1i*Mvc*sin(Pvc)))/3;
% Detect symmetrical fault
    if ((Mia>0.09)&&(Mib>0.09)&&(Mic>0.09))
        PHI=phase(V1)*180/pi-phase(I1)*180/pi-aline
        if ((PHI>205)&&(PHI<295))||((-55>PHI)&&(PHI>-
145))
            Direction=2%reverse fault
        else
            Direction=1%forward fault
        end
    end
% Detect unsymmetrical fault
     if ((Mia>0.09)||(Mib>0.09)||(Mic>0.09))
           T32Q=abs(V2)*abs(I2)*cos((-phase(V2)*180/pi-
phase(I2)*180/pi-aline)/180*pi)
           Z2=V2*(cos(aline*pi/180)+1i*sin(-
aline*pi/180))/I2;
           PHI=phase(V1)*180/pi-phase(I1)*180/pi-aline
        if ((PHI>205)&&(PHI<295))||((-55>PHI)&&(PHI>-
145))
                 Direction=2%reverse fault
             else
                 Direction=1%forward fault
        end
     end
    end
        break

    if Mia<0.09&&Mib<0.09&&Mic<0.09
             Direction=0% No fault
              fwrite(udpN,Direction);
    end
%Send fault direction information to Relay 2
      fwrite(udpN, Direction);
     i = i +1
    saveIA(:,i)=IA;
    saveZ2(:,i)=Z2;
  fwrite(udpN, Direction);
```

```
if i==200
     break
 end
end
% Relay 2 setting
% Set Port for sengding trip signal
r=serial('COM7','BaudRate',115200)
fopen(r)
% Build connection between DAQ and computer
d=daq.getDevices;
s = daq.createSession('ni');
addAnalogInputChannel(s,'Dev1',0,'Voltage');
addAnalogInputChannel(s,'Dev1',1,'Voltage');
addAnalogInputChannel(s,'Dev1',2,'Voltage');
addAnalogInputChannel(s,'Dev1',3,'Voltage');
addAnalogInputChannel(s,'Dev1',4,'Voltage');
addAnalogInputChannel(s,'Dev1',5,'Voltage');
% Set DAQ scan rate and time
s.Rate =1280;
s.DurationInSeconds = 1/60;
fwrite(r, bin2dec('00000000')) % Relay 2
%Build wireless communication using UDP protocol
udpN= udp('192.168.1.2', 9090, 'LocalPort', 9091);
fopen(udpN);
%Reset the trip signal
fwrite(r, bin2dec('00000000')) % Relay 2
relay1 = 90
relay2 = 90
time=200;
i=0
aline=50;
D = [];
A=0;
Direction=0;
flushinput(udpN)
% Run the main loop program
    while(1)
    fwrite(udpN,10);
    if fread(udpN) == 12
% Record the line data
```

```
    data = s.startForeground();
    IA=data(:,4);
    IB=data(:,5);
    IC=data(:,6);
    VA=data(:,1);
    VB=data(:,2);
    VC=data(:,3);
% Use fast Fourier transform to get fundamental values
    Ia=fft(IA,64);
    Ib=fft(IB,64);
    Ic=fft(IC,64);
    Va=fft(VA,64);
    Vb=fft(VB,64);
    Vc=fft(VC,64);
    Mia=(abs(Ia(4)));
    Mib=(abs(Ib(4)));
    Mic=(abs(Ic(4)));
    Mva=(abs(Va(4)));
    Mvb=(abs(Vb(4)));
    Mvc=(abs(Vc(4)));
    Mia=Mia/32;
    Mib=Mib/32;
    Mic=Mic/32;
    Mva=Mva/32;
    Mvb=Mvb/32;
    Mvc=Mvc/32;
    Pia=phase(Ia(4));
    Pib=phase(Ib(4));
    Pic=phase(Ic(4));
    Pva=phase(Va(4));
    Pvb=phase(Vb(4));
    Pvc=phase(Vc(4));
    aa=cos(2*pi/3)+1i*sin(2*pi/3);
% Calculate positive sequence component, negative
sequence component and zero sequence component

I0=((Mia*cos(Pia)+1i*Mia*sin(Pia))+(Mib*cos(Pib)+1i*Mib
*sin(Pib))+(Mic*cos(Pic)+1i*Mic*sin(Pic)))/3;
```

```
I1=((Mia*cos(Pia)+1i*Mia*sin(Pia))+aa*(Mib*cos(Pib)+1i*
Mib*sin(Pib))+aa^2*(Mic*cos(Pic)+1i*Mic*sin(Pic)))/3;

I2=((Mia*cos(Pia)+1i*Mia*sin(Pia))+aa^2*(Mib*cos(Pib)+1
i*Mib*sin(Pib))+aa*(Mic*cos(Pic)+1i*Mic*sin(Pic)))/3;

V0=((Mva*cos(Pva)+1i*Mva*sin(Pva))+(Mvb*cos(Pvb)+1i*Mvb
*sin(Pvb))+(Mvc*cos(Pvc)+1i*Mvc*sin(Pvc)))/3;

V1=((Mva*cos(Pva)+1i*Mva*sin(Pva))+aa*(Mvb*cos(Pvb)+1i*
Mvb*sin(Pvb))+aa^2*(Mvc*cos(Pvc)+1i*Mvc*sin(Pvc)))/3;

V2=((Mva*cos(Pva)+1i*Mva*sin(Pva))+aa^2*(Mvb*cos(Pvb)+1
i*Mvb*sin(Pvb))+aa*(Mvc*cos(Pvc)+1i*Mvc*sin(Pvc)))/3;
% Detect symmetrical fault
   if Mia>0.09&&Mib>0.09&&Mic>0.09
       PHI=phase(V1)*180/pi-phase(I1)*180/pi-aline
       if ((PHI>70)&&(PHI<160))||((PHI>-290)&&(PHI<-
200))
           Direction=1;%forward fault
       else
           Direction=2;%reverse fault
       end
   end
% Detect unsymmetrical fault
   if Mia>0.09||Mib>0.09||Mic>0.09;
           T32Q=abs(V2)*abs(I2)*cos((-phase(V2)*180/pi-
phase(I2)*180/pi-aline)/180*pi);
             PHI=phase(V1)*180/pi-phase(I1)*180/pi-aline
            if T32Q>0;
     if ((PHI>70)&&(PHI<160))||((PHI>-290)&&(PHI<-200))
                Direction=3;%forward fault
            else
                Direction=4;%reverse fault
     end
            end
   end
  if Mia<0.09&&Mib<0.09&&Mic<0.09
            Direction=0; % No fault
```

```
   end
% Transfer Values into var
   relay1 = fread(udpN);
   relay2 = Direction;
   i = i + 1;
   fprintf('Cycle= %i \n',i)
   fprintf('relay 1= %i \n',relay1)
   fprintf('relay 2= %i \n',relay2)
   disp(' ')
% Trip logic
  if ((((relay1 == 1) && (relay2
==4)))||((relay1==1)&&(relay2==2)))
  fwrite(r, bin2dec('10001000')) % Relay 2
  fwrite(r, bin2dec('00000001')) % Relay 1
  disp('Break Program')
  break;
  else
  (Direction && direction2 ~= 0);
  fwrite(r, bin2dec('00000000')); % Relay 2
  end
  if i == 200;
     break;
    end
   end
 end
```