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Voltage dip mitigation for motor starters using an adaptive high speed relay protection on the high voltage transmission system

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VOLTAGE DIP MITIGATION FOR MOTOR STARTERS USING AN ADAPTIVE HIGH SPEED RELAY PROTECTION ON THE HIGH VOLTAGE TRANSMISSION SYSTEM

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ABSTRACT

Currently, the aging state of the protection systems for industrial facilities is calling for a system-wide review of the equipment and the protection schemes[1] used in all these places, calling for a new approach in the design and implementation of these systems. Some of these facilities house critical processes that can be seriously affected by a misoperation of equipment or a disturbance in the system, aspects ranging from safety of plant workers to millions of dollars in loss of production.

In this thesis different contingency situations were explored for problems in the utility transmission system that could affect large industrial facilities with continuing critical processes. Different situations were analyzed including, but not limited to, disturbances caused by momentary short circuits and different types of faults in the system. In this thesis for each scenario, one communication aided protective scheme was developed to provide the best adaptive protection to meet the needs of the industrial plant and automatically adapt and protect the industrial facility, and basically keep the electric equipment running.

The developed protection scheme then was verified in comparison between one test case using digital simulation by ASPEN ONELINER and using a DOBLE power system simulator on one open loop case simulation using a real scale model with real time data acquisition.

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[1] Schemes: Implementations of a certain protective relay philosophy or application

CHAPTER 1: INTRODUCTION

1.1 Introduction

Problems associated with the reliability of the utility power system have been an important driving factor in determining more efficient and faster protective relaying schemes necessary to ensure the normal operation of the industrial site. Critical failure events, especially natural disasters in the area, cannot be completely prevented. Nevertheless, the impact of short duration changes in the system that usually is more frequent than complete outages can be mitigated by the use of relay protective systems. This chapter will introduce the concepts of voltage dips, occurrences in the transmission system that we are going to analyze in subsequent chapters, and a brief description of what an adaptive protective relay implies and how it fits in the power system protection area.

1.2 Voltage Dips

By definition, voltage dip can be categorized as the reduction of voltage associated with an occurrence of a short circuit or other extreme increase in current like motor starting or transformer energizing. A voltage dip is characterized by its magnitude and duration. Basically, fault types, source and fault impedances define the dip magnitude, whereas fault clearing time defines the dip duration.

Dip magnitude is considered here as the remaining voltage RMS during the dip. Fault clearing time is the time needed by the protective device and the breaker or breakers associated with that protective device to clear the fault. Transformer connection

will also affect dip magnitude sensed by customer at secondary side during a fault at primary side.

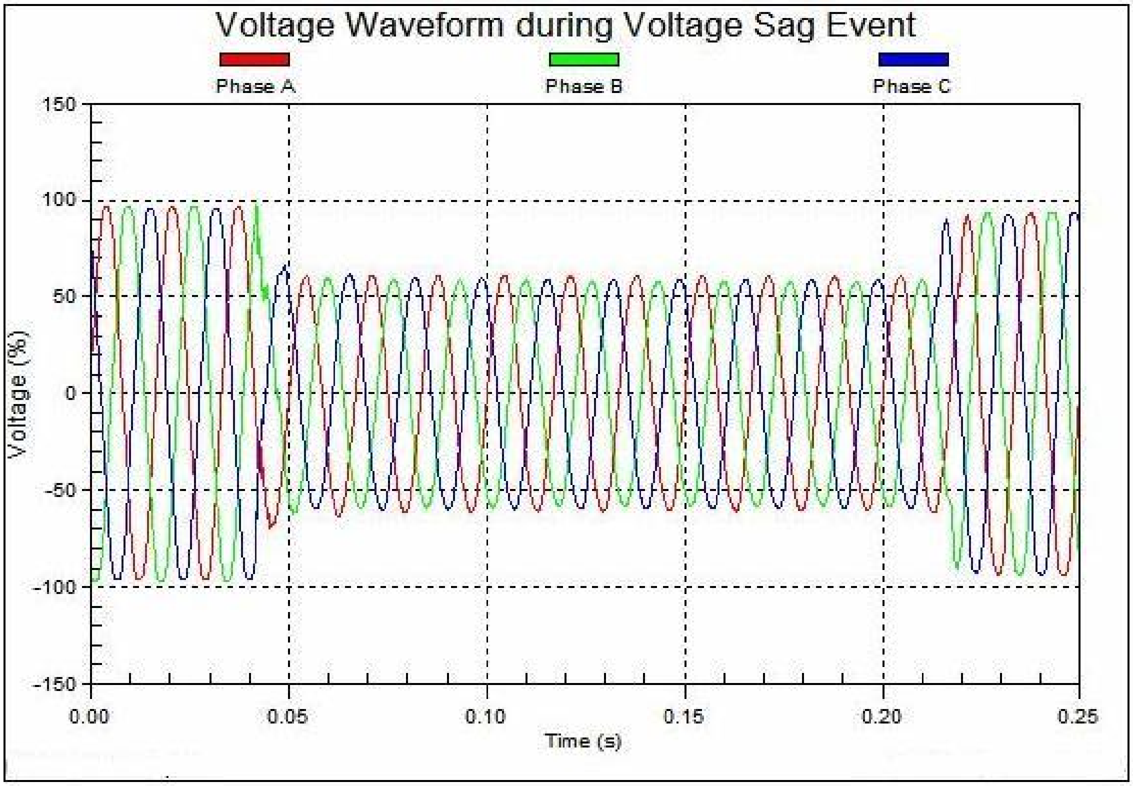

Fig. 1.1 Voltage dip during a 3-phase fault [14]

In Figure 1.1, the voltage RMS reduction in all three phases can be appreciated and how as the protection scheme clears the fault how the voltage recovers to its normal level.

In the occurrence of a voltage dip, an induction motor may stall and may not be able to accelerate the load connected to it while it tries to come back to normal with a restored supply voltage.

Considering only the characteristics of the induction motor at the moment, the voltage dip will reduce the motor torque proportional to the square of the motor terminal

voltage. The slip will increase proportional to the current. All these aspects related to the voltage dips and response of induction motors will be explored in Chapter 2.

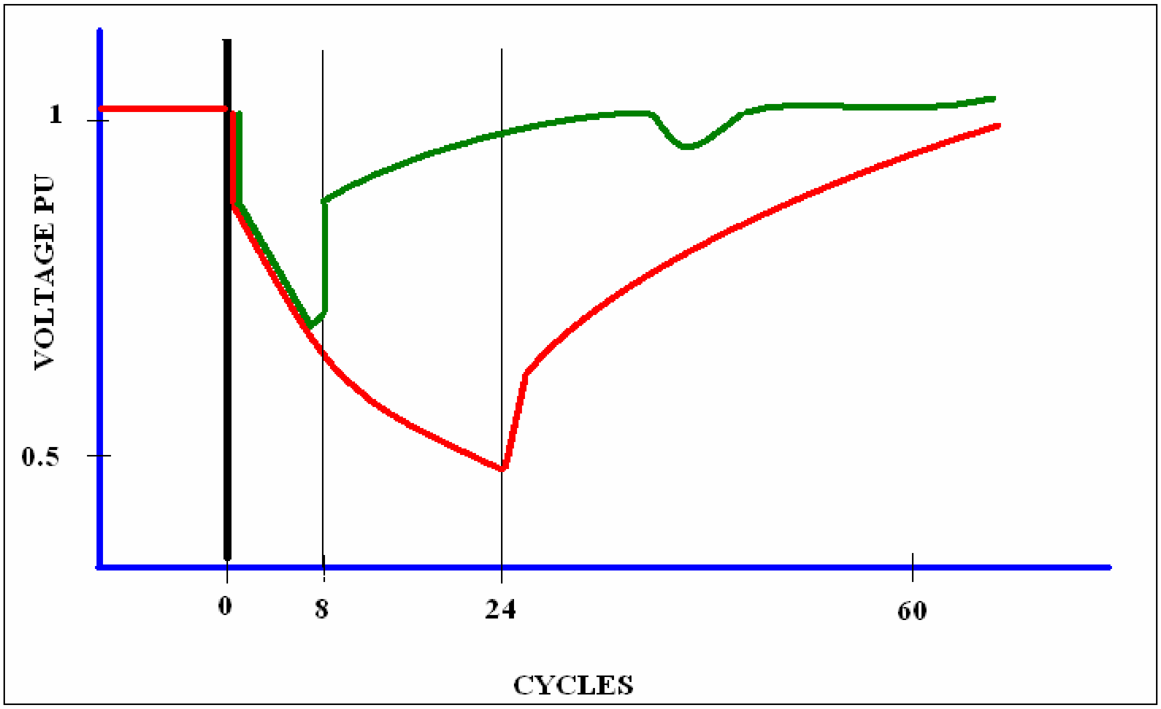

Fig. 1.2 Fault voltage dip and voltage recovery, fault cleared in 8 cycles and 24 cycles [2]

Figure 1.2 shows the initial voltage dip and its recovery on the voltage profile of the medium voltage motor controller for a three-phase fault in the utility system, cleared in 8 cycles and 24 cycles. In [2], an extremely efficient method of voltage protection is presented, but his study only applied the theoretical figure of how much the voltage should dip in order to sustain the fault event.

1.3 Electric Power Transmission System Protection

Electric power systems encompass many components and many devices distributed along great distances. It serves the process of delivering reliable electricity to consumers.

These electrical grids use devices like relays, fuses and other types of protection elements to detect and remove abnormal conditions as fast as possible.

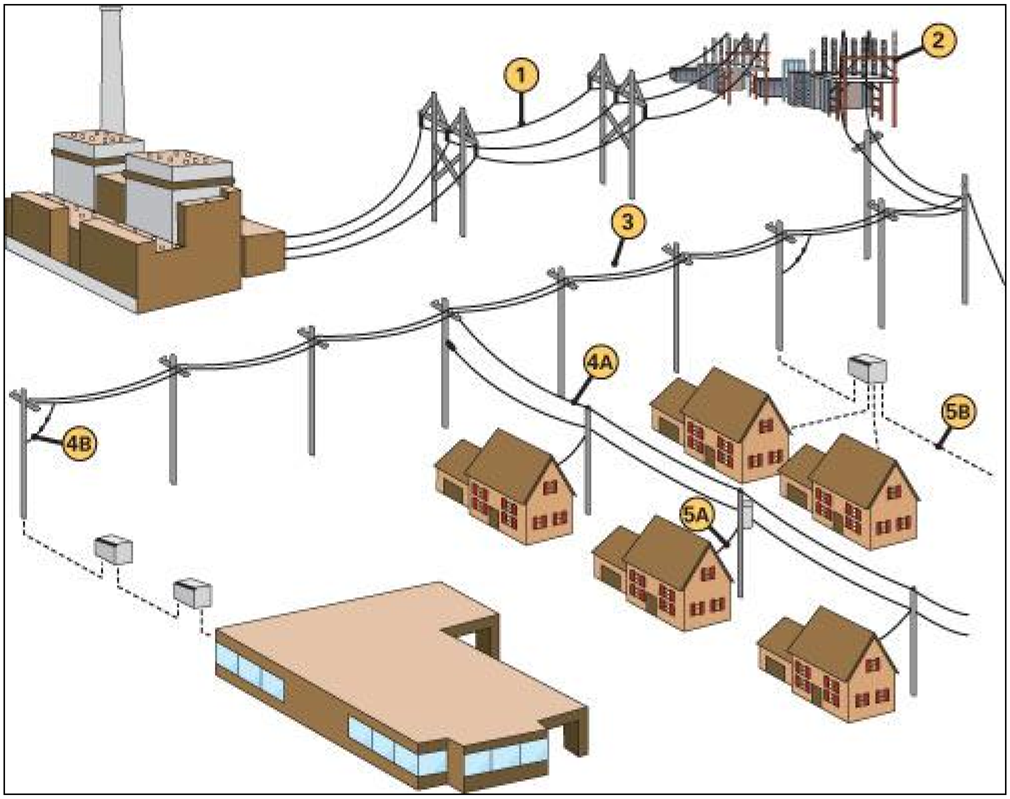

Fig. 1.3 How electricity gets to homes and industries [18]: Electricity is generated at power plants, and is sent out on high voltage transmission lines ❶ to substations which adjust the electrical voltage so it can be routed to the lower voltage more accessible lines❷, then power is delivered through these lines ❸ to major industrials and homes ❹ ❺.

The removal of abnormal conditions will isolate faulted segments of the power system. This way, the unfaulted portion can continue serving all connected loads without damaging any equipment, which is the reason why operating time is a key element in the power system protection, where time is usually measured in milliseconds. Traditionally, protective relays have been electromechanical base, with moving parts that activate

breaker tripping. These devices proved to be limited in their flexibility to perform multiple relaying functions, ability to adapt to different conditions, and communication to other remote devices.

In the last thirty years, the microprocessor relays have gained acceptance over the solid state and the electromechanical ones in the industry and they are becoming the preferred practice in relaying applications. Microprocessor relays are very flexible in terms of the variety of relaying practices they can implement. The SEL-421 [14] microprocessor relays will be presented in this thesis.

1.4 Adaptive Power Protection

The concept of adaptive relaying tends to demonstrate how simple adaptive relaying schemes can be used as baseline techniques for reconfiguring protective devices in a power system. Adaptive relaying refers to the updating of the power system's protective devices to correctly change its setting and/or relaying logic upon a change in the transmission system conditions, an external signal or other events.

This thesis will outline the process of developing an effective adaptive protection schemes for transmission power systems feeding large industrial complexes. The idea is to determine the viability of having such scheme and if the method used is appropriate, in this case the use of a SEL-421 [14]. Types of adaptive relaying are adaptive distance protection, power transformer protection, adaptive reclosing, under-frequency protection and fast communication aided schemes. More specifically, adaptive protection is applied to determine dynamically pickup currents and time multiplier in overcurrent relays, for determining dynamic zones of protection with distance relays using fiber

communications. All these parameters are calculated for normal load conditions and worst case conditions as well.

1.5 Thesis Organization

This thesis is organized as follows: First, an introduction to the concepts of microprocessor relays and how they operate, second the development and testing of the adaptive protection scheme, finally a discussion of the results and future work.

1.5.1 Thesis Objective

The objective of this thesis is to create and show how the protection scheme allows the local utility transmission system to maintain reliable power conditions at the industrial facility and clear momentary short circuit fault conditions on the transmission system before the motor controllers drop out and the AC motors start to shut down

1.5.1 Thesis Structure

Chapter 2 presents fundamentals on microprocessor relays and motor controllers in a typical industrial facility. The protective relaying development will be showcased and some introductory background on the tools used in this project

. Chapter 3 presents the actual development of the protection schemes, one communications aided schemes via fiber optics (FO). This POTT (Permissive Overreach Transfer Trip) scheme will be based on a typical network

In Chapter 4, dropout times will be tested in a real simulation using a scale model with real motor controllers. Motor controllers will be subjected to voltage dips and all dropout times will be recorded for different conditions.

And finally Chapter 5 will present all results and conclusions. It also will provide a summary of the benefit of this work and potential future studies.

CHAPTER 2: CONCEPTS AND PROBLEM BACKGROUND

2.1 Introduction

For many years, distance relaying was the preferred technique for transmission lines protection. This approach was very popular given the fact that in the old days, the electric grid was mainly composed of very long transmission lines and also very weak sources. This structure gave the distance relaying scheme a very robust base to operate, but as the years went by, the electric grids found that their transmission lines started to become shorter an shorter with the addition of new substations to serve a new industrial facility, a new subdivision of homes, etc. This trend created a problem for the distance relaying specially with the changing SIR (source-to-line impedance ratio) and the new multiple sources of infeed[2], a new source of fault current between the relay location and the fault location. All these transmission line relaying concepts are going to be introduced, a brief background on relays and motor contactors will be exposed and finally the problem statement will be presented. Non-pilot[3] schemes versus pilot scheme will be explored as well.

2.2 Relays

Relays are protective devices that observe a scaled version of the line voltage and current and control whether or not the system being monitored should continue to operate in its current state. Relays are essentially the pillars for the safe and reliable operation of power systems. The first protective relays used in power systems were mechanical devices. They were based on mechanical principles and had moving parts that included

[2] Infeed: a source of fault current between a relay location and a fault location.
[3] Pilot: Relaying scheme that uses a communication channel to send information from the local relay terminal to the remote relay terminal

springs, rotors, and solenoids. Scaled line voltages and currents were used in these relays to actuate the moving parts. When a line current was too high or voltage was not within limits, the mechanical parts of the relay would interact to close or open a set of contacts. This, in turn, could affect a larger collection of different relays and result in operating a switch in the power system. An important issue in the operation of these relays is their maintenance. Given the existence of a great number of moving parts and components like capacitors that needed to be replaced or calibrated and their operation is not sufficiently reliable. Fig 2.1 shows an old electromechanical relay, with the different elements, this one in particular, for phase faults. In the old electromechanical world, phase relays, overcurrent and ground relays were separate units on the same panel. Nowadays, microprocessor relays have all these devices combined in one box.

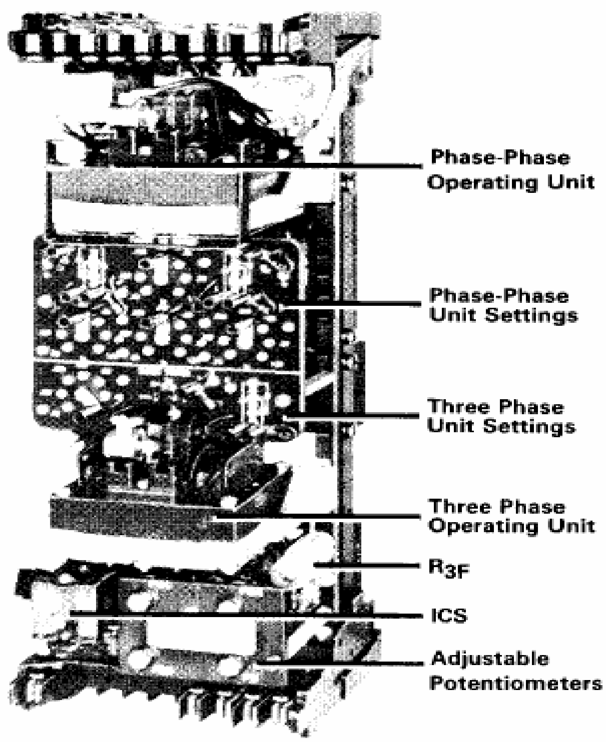

Fig. 2.1 ABB KD-10 electromechanical type relay, the most popular relay of the 1960's and 70's

Analog relays are still in use today, but during the past twenty years the microprocessor relay has become increasingly popular, and lots of these old relays have been replaced. Digital relays are protective devices that are based on microprocessors for switch control. Power electronics are used to discretize the scaled line voltage and current signals, which the microprocessor can sense and use to implement the control algorithm. They also possess really advanced software interface that allows the engineer to perform multiple levels of remote control and communication.

Communications is an important benefit of digital relays. Microprocessor relays can easily communicate between each other across long or short distances. The addition of communication to protective relaying greatly increases the power of a protection scheme. This thesis work will prove this assumption by developing fast communication aided schemes will prevent momentary disturbances in the transmission system from affecting the motor controllers in the industrial facility. Typical fiber optics setup below:

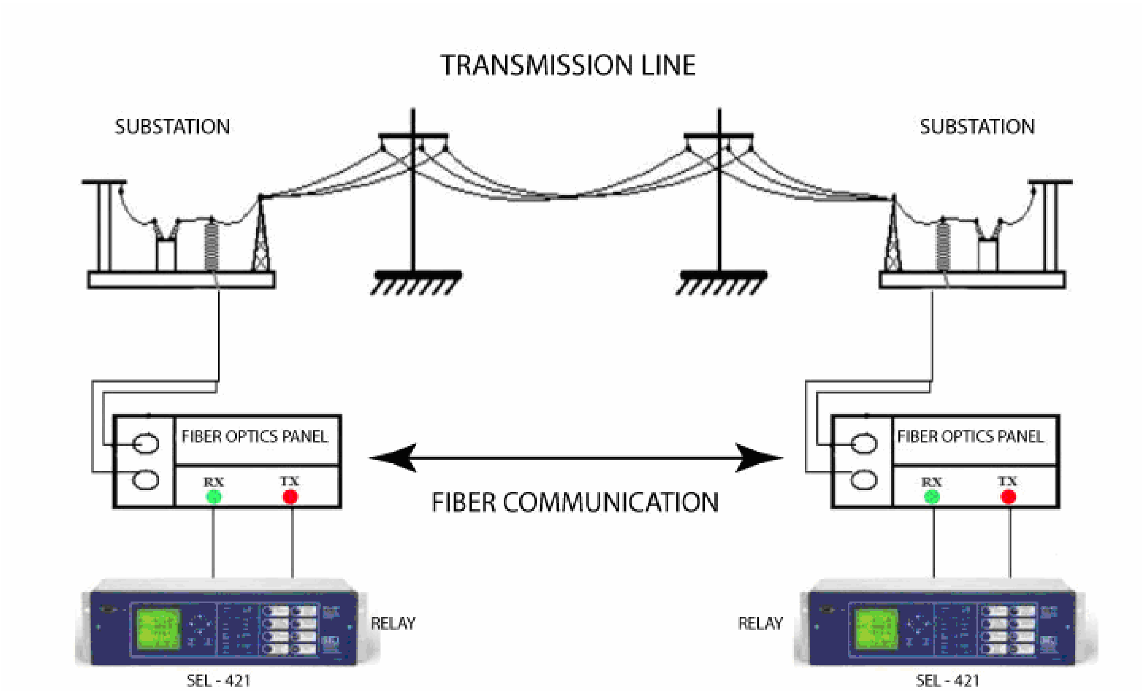

Fig. 2.2 Microprocessor relay communication

In addition, relays operate based on specific characteristics, more specifically, operating characteristics that the relays based their decision on. In Figure 2.3, the two most important operating characteristic of the protective relays are shown, the R-X diagram and the time-current diagram.

These two characteristics will guide the relay through the decision making process of operation. In the time-current case, the relay will operate in the specific situation where the values being fed to it from the system fall into the region of operation. In the R-X diagram case, several zones of protection represented by multiple mho characteristics will entail a specific action from the relay. This will be explained more in depth in this chapter.

These two characteristics spawned all different types of relays depending on the needed application: phase overcurrent relays, ground overcurrent relays, directional overcurrent relays phase distance relays and ground distance relays. In the past, all these relays were separate units in the same relay terminal, nowadays microprocessor relays are so smart one unit can replace all these relays and merge all these units into the same box.

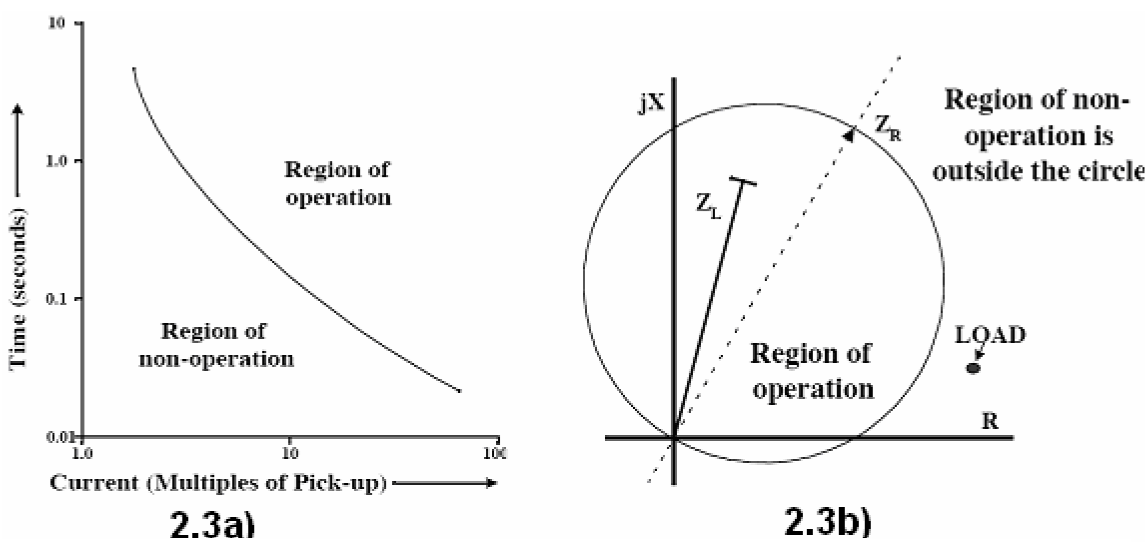

Fig. 2.3. Extremely inverse time overcurrent characteristic 2.3a) and R-X diagram showing the mho circle and the non-operation zone 2.3b). The region of operation is the trip region of the relay.

2.3 SEL-421

The SEL-421 [14] is the relay that was proposed in this project for purposes of transmission line protection. It allows the user to apply a complete pilot protection, 100% line coverage. One of its more important features is the ability to communicate over fiber optics using Schweitzer's mirror-bit[4] technology. This system will provide the communication-aided relaying needed to clear the fault in less than 10 cycles. Later it will be demonstrated the threshold where the motor controllers start to drop the motor loads. It possesses many relay elements built in the same box, directional overcurrent elements, phase distance elements, ground distance and overcurrent elements, etc. It also performs many functions that in near future will become the pillar of the new industry trend to have synchophasors measurement across the grid to monitor system stability.

Fig. 2.4 SEL-421 microprocessor relay [14]

2.4 Transmission Line Relaying Principles

Selection and development of line relaying protection requires the consideration of several factors. For protection purposes, a "line" is defined by the location of the circuit breakers and all electrical apparatus like breakers, line switches, line traps, etc that fall into that area. That means that the relays located at each end of the line will be

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[4] Mirror-Bit: Relay to relay communication protocol that sends internal logic stauts, enconded into a messag form one device to another.

reading voltages and currents on the line side through current and potential transformers, CTs and VTs, which will take all the real world quantities and scaled them down to manageable quantities that the relays can handle.

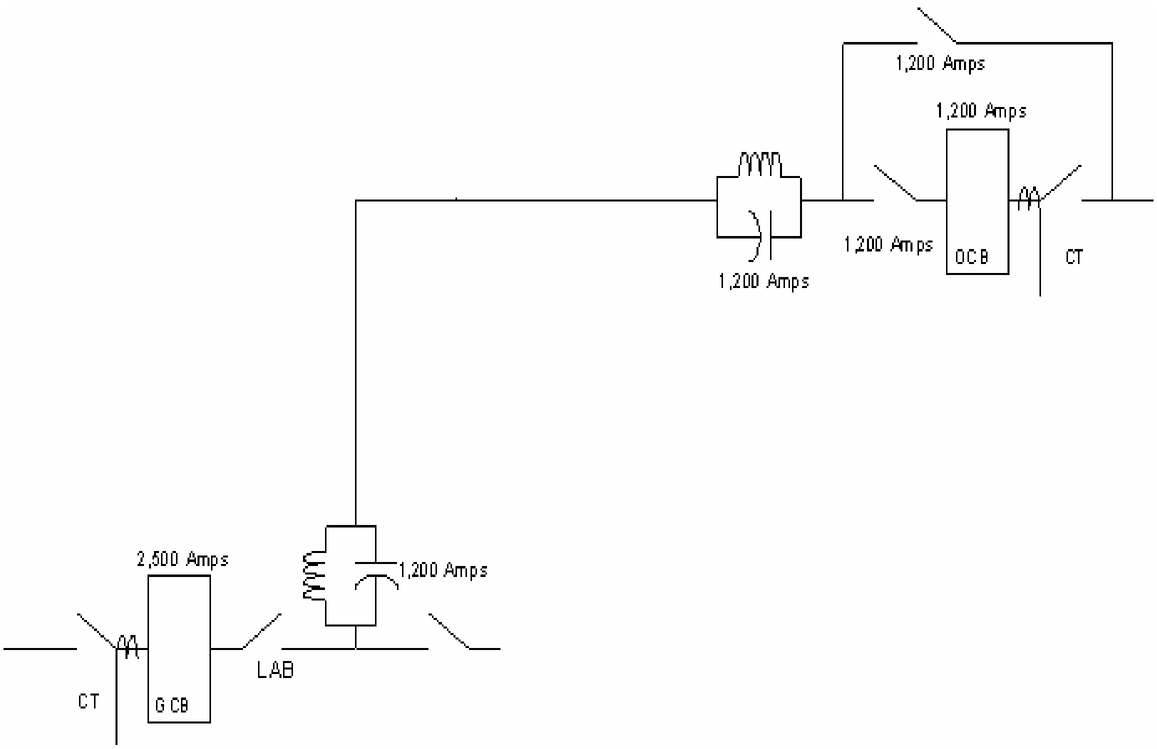

Fig. 2.5 Definition of line for relaying purposes

As shown in Figure 2.2, Relays 1 and 2 will provide back to back protection to the transmission lines, the same as Relays 3 and 4.

The line relaying process for a given application then it is determined by several factors described in the table below, but the most important of all will be the criticality of the line. This refers to the desired level of reliability on transmission line protection that certain area of the utility's power system might justify, for example serving a very important industrial load. Therefore, in thesis work, the most reliable communications aided pilot scheme will be used for the protection of the transmission lines.

Table 2.1 Line relaying application considerations

SYSTEM FACTORS	DESCRIPTION	IMPACT
Fault clearing times requirements	This requirement refers to the effect of voltage dips and system stability in the system, whereby the clearing time consideration will be the most important factor in terms of type of communications used.	Motors and sensitive equipment might b affected by the duration of a fault event in the transmission system. Fast tripping is necessary to avoid dropped out motors.
Line length	Short lines and very long lines will require a special approach depending on the relay application desired, especially in terms of costs.	Communications costs associate with the circuit (cost-benefit relationship between having fiber optics, most reliable, and some other cheaper communication medium)
Strength of sources	Interrelated with the line length aspect is the strength of the sources to a transmission line. Source strength determines available fault current strength and affects the ability of the protective device to see what really is happening in the system	Weak systems with no close generation or vice versa may present a challenge on how the sensitiveness of the relay is set
Line configuration	Special cases like tapped loads along the line or series capacitors may call for a special ray application in such cases	Special applications like series capacitors may represent a challenge especially for voltage reversal occurrences and for zero sequence current sources tapped in the line.
Line loading	Very heavy line loading may require special protection specially load-blinding features that prevent the larger zones of protection from tripping	Far looking zone 3 reaches might b affected by heavy loading, relay must be adapted for this conditions

Communications, protection operation choice, backup considerations, reclosing, and redundancy would be the next steps in the selection and development of the relaying application desired. The choice of communication may be influenced by several factors, but the decision will come down to the criticality and the protection requirements on the relaying system.

Some compromises will have to be made in the design of the protective relaying system. Reliability by definitions is a combination of dependability and security [10]. Other factors that need to be taken into account are reliability versus cost [10], and speed requirements. All these factors will affect the final design decision and some compromises that are unavoidable. For his thesis work, we are going to choose the POTT (Permissive Overreaching Transfer Trip) communications aided transmission relaying, with adaptive zones of protection. Later in this Chapter the difference between communications aided relaying and stand alone relaying which will be used in this thesis against distance relaying are will be explored in more depth. Redundancy and reclosing methods will add many benefits to our desired protective scheme, different approaches to endure reliability issues such as redundant CTs and VTs, redundant DC sources for the trip coils and local backup relays.

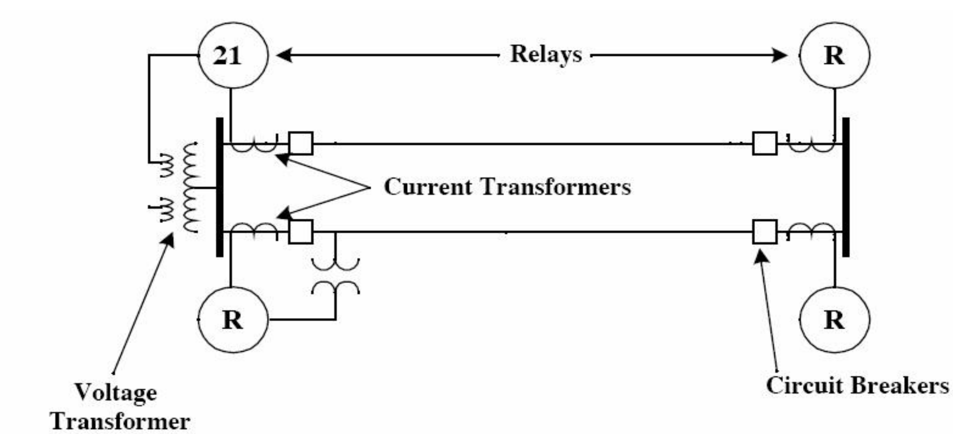

Fig. 2.6 Normal two-bus, parallel relaying system configuration

Reclosing is very important issue as well, depending on the system voltage; the reclosing method can range from a high Speed with no intentional delayed method with synchronism and/or undervoltage in the line/bus supervision on high voltage transmission systems, to blind to or three shots from either end of the line in lower transmission systems.

2.4.1 Step Distance Relaying

Step distance relaying is the non-pilot application of distance relaying protection and it was the most popular system in the electromechanical world. Several zones of protection are employed for this task as shown in Figure 2.5 and described using the R-X diagram as shown in Fig 2.6.

Zone 1 is set to trip with no intentional delay and its set approximately 80-90% of the transmission line impedance. The main reason behind this percentage is to prevent the relay to overreach and trip for short circuit faults past the next relay terminal.

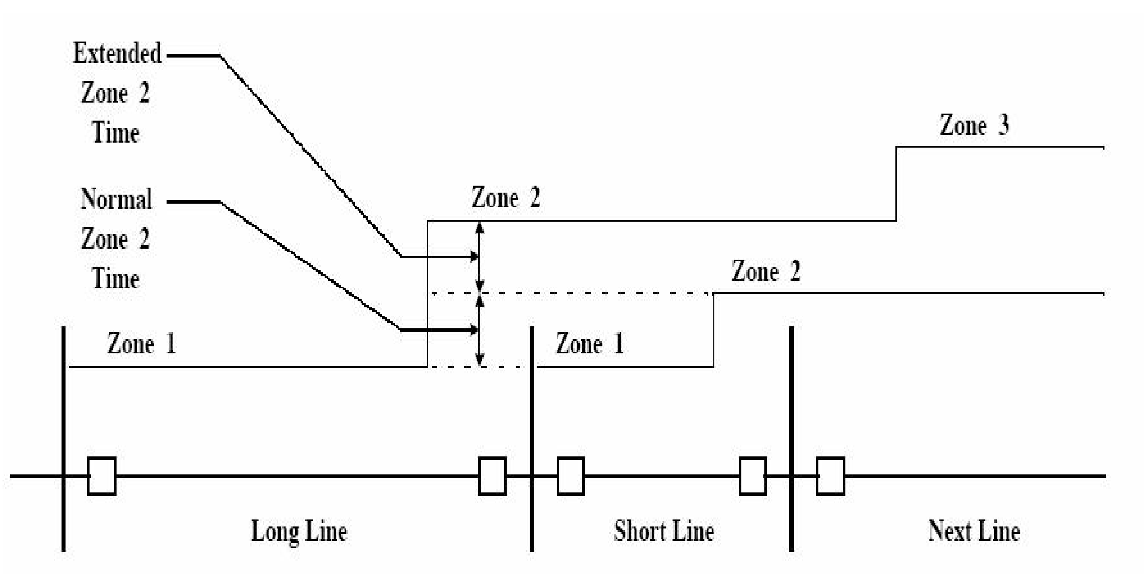

Fig. 2.7 Zones of protection on short and long transmission lines.

The minimum reach of the second zone, designated Zone 2, is typically 120% of the protected line impedance, providing full coverage to the protected line and ensuring that this setting will not overreach any Zone 1 setting. This zone has an intentional time delay typical in the rage of 15-30 cycles depending on the application; it might be set faster or slower. This time delay prevents instantaneous clearing of the local terminal for a fault past the remote terminal. On communication aided scheme this time delay may be shorter. The reach of this setting may vary considerably depending on the application.

Although Zones 1 and 2 fully ensure 100% coverage on the protected line, an additional Zone 3 forward and reverse looking setting may be necessary to provide backup features for Zone 2 at the local terminal and for the failures in the remote terminals. Ideally, the zone 3 setting would provide coverage for all the protected line, plus all the next longest lines leaving the station, but under heavy load conditions, there might be an insufficient margin to ensure that Zone 3 would undesirably enter on its operating characteristic of the distance relay. If load conditions are a problem, a form of sequential tripping might be useful, typically using the protective relays of the remote terminal to remove the infeed effect, and then allow the Zone 3 reach to be applied.

The step distance concept uses no communication or interaction with the relay at the remote terminal which makes it very slow in some cases. For this work, a very high speed tripping scheme will be used, still falling into the same concepts of protection zones but improving the time delay on all the reaches. Step distance schemes are very popular in applications for very long transmission lines, in fact, it makes it very cost prohibitive to have some kind of communication, fiber optics or some other kind, to provide adequate protection to the line.

2.4.2 PUTT AND POTT Schemes

PUTT (Permissive Underreach Transfer Trip) requires both, Zone 1 underreaching region, and Zone 2 overreaching region. Phase distance elements are used exclusively for multiphase faults, while ground distance with directional overcurrent supervision may be used to detect phase to ground faults. The Zones of protection must overlap, to ensure that all the transmission line is protected and there are no blind zones where faults won't be detected. Both terminals share a fiber optics communications channel. This channel will transmit a continuous GUARD signal to maintain communication and provide monitoring of the channel. The relay automatically will adjust its zones of protection if the GUARD signal is not received, because that will entail a Loss of Communication situation. This scheme will trip in approximately 4-5 cycles for an internal fault within the overlapped Zone 1 regions, the Zone1 element will operate and trip the breaker directly; at the same time each end will transmit a TRIP signal that will also initiate breaker tripping.

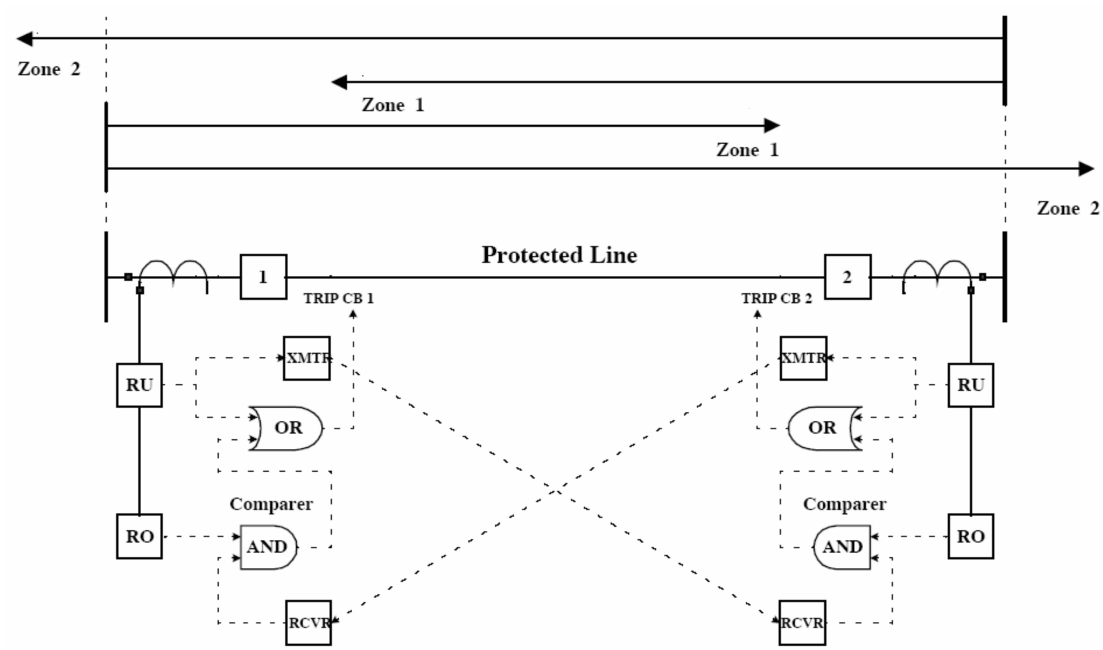

Fig. 2.8 PUTT scheme

The same procedure would be followed for external faults falling in the Zone 2 overlapping regions. As soon as confirmation from the remote end is received that there is a reverse fault, the relay will wait for the correspondent relay terminal in that direction to trip first, otherwise that relay reverse backup protection would some into play.

POTT scheme will follow the same philosophy but it would only require an overreaching zone of protection. As for the PUTT scheme, phase distance would be used only for multiphase fault detection while ground distance would be use for detection of phase to ground faults.

The GUARD frequency will be sent in a standby fashion to monitor communication while overreaching would cause the TRIP signal to be keyed to the remote side. Combined wit the protected region output, the comparator will produce an output to initiate tripping.

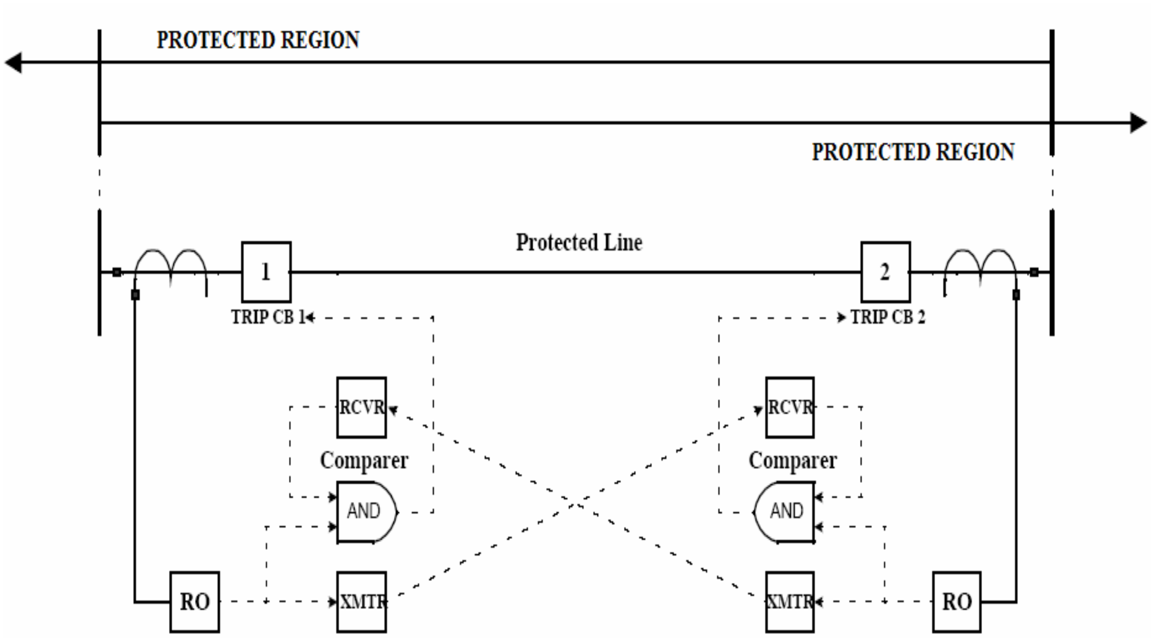

Fig. 2.9 POTT scheme

This project will provide a combination of a POTT scheme with zone acceleration adaptive relaying, given certain disturbances in the transmission system, the adaptive zone acceleration will speed up or delay the relay operation.

2.5 Motor Controllers

Motor starters receive the power service and direct it accordingly to the appropriate motors to perform useful work efficiently. Typical functions performed by a motor controller include starting, accelerating, stopping, reversing, and protecting motors. Most AC motors, 600 V or less, are started directly across the supply lines. There are two basic types of under-600V motor controllers: magnetic starters and manual starters. For this thesis, magnetic starters are going to be the only type covered for the study.

2.5.1 Induction Motors

Most AC motors are induction motors; they are favored for their ruggedness and simplicity. In fact, 90% of all the loads used in an industrial facility are induction motors. The stator windings of induction motors are connected to the power line. Energy is transferred to the rotor by means of the magnetic field produced by the current and induction afterwards. Depending on the type of power supply, the start winding is either polyphase (usually three phase) or single phase. In the wound rotor induction motor, the conductors of the rotor winding are insulated and brought out to a slip ring, where all are connected to a starting or control device. All motors require these control devices to perform very specific tasks like: stator disconnect, stator fault interrupt, and stator switching. Motors are essentially a constant MVA load, a balanced lowering of the voltage is accompanied by a balanced increase in the line currents, consequently, for small voltage drops of long duration, the thermal protection and undervoltage inherent

protection of the motor controller should be enough to ride it out, but when there are large voltage dips, specially in motors controlled through NEMA[5] starters, this will require additional protection.

In this thesis, the intent is not to explore deeply into the induction motor basics given the fact that the only interest for experimental purposes is motor starters.

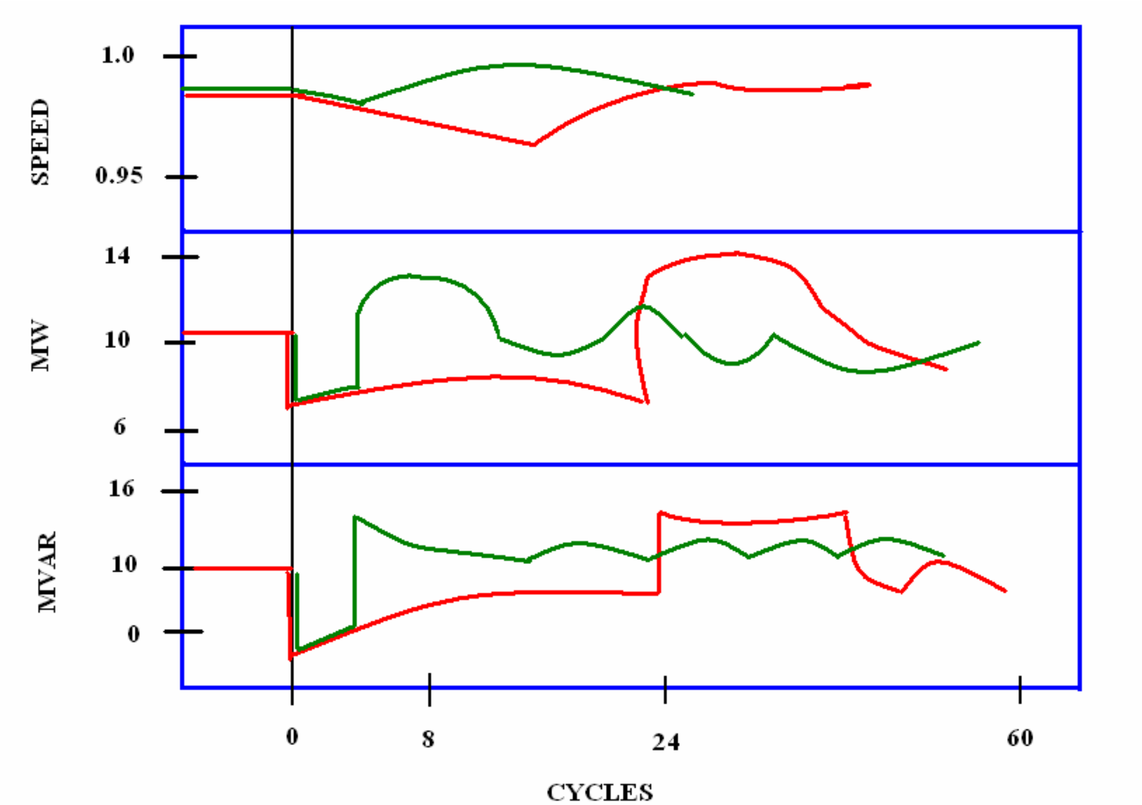

Fig. 2.10 Speed, MW, and MVAR transients of an equivalent induction motor due to voltage dip and then recovery from Fig 1.2, initial state is normal load [2]

Figure 2.7 shows the speed, MW, and the MVAR transients of one 11 MW induction motor. These transients are associated with the voltage dip and voltage recovery shown in Figure 1.2.

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[5] NEMA: National Electrical Manufacturers Association, a forum for technical standards that are in the best interest of the industry, with approximately 450 member companies.

2.5.2 Magnetic Starters

A magnetic starter is basically an electromagnetic on-off switch which starts a motor when voltage is applied to its magnet coil and stops the motor when voltage is applied to its magnet coil and stops the motor when voltage to the coil is disconnected.

Since motors are rated in voltage, horsepower and current, starters and contactors are selected in accordance with these ratings. Most motors run on voltages less than 600V, so the majority of starters and contactors controlling them are designed to operate up to the 600-V level. They are usually rated at 600-V maximum. Therefore, motor controllers have been rated to carry current continuously up to a specific range from 9 to 1215 A. NEMA standard sizes and their corresponding ratings are shown in Table 2.3.

Table 2.2 NEMA Standard for Low-Voltage contactors

Maximum Horsepower (hp)										
NEMA Size	NEMA Continuous Amp Rating	Full Voltage Starting			Part Winding Starting			Wye Delta Starting		
	(Amp)	200V	230V	460V 575V	200V	230V	460V 575V	200V	230V	460V 575V
00	9	1.5	1.5	2						
0	18	3	3	5						
1	27	7.5	7.5	10	10	10	15	10	10	15
2	45	10	15	25	20	25	40	20	25	40
3	90	25	30	50	40	50	75	40	50	75
4	135	40	50	100	75	75	150	60	75	150
5	270	75	100	200	150	150	350	150	150	300
6	540	150	200	400		300	600	300	350	700
7	810		300	600		450	900	500	500	1,000

2.5.3 Problems on Motor Starters Caused by Voltage Dips

Motors controlled by magnetically-held starters with three or two wire control may trip on voltage dips, as the contactor may drop out on 20% to 70% of the supply voltage. This situation may represent a very serious challenge because of the nature of the motors.

When the motor is disconnected from the source voltage, the motor continues its normal operation unvarying in amplitude and frequency. However the motor terminal voltage does change, the total rotating inertia acts a prime mover and delivers energy to the connected load. While this happens, deceleration in the rotating mass results. Prior to the voltage interruption, the rotor and the stator are tying to operate in synchronism in accordance to the load-torque angle. When the motor is disconnected, the rotor of the motor immediately starts to decelerate at a rate determined by the rotating inertia and the load characteristics. The frequency of the motor's voltage starts decreasing. Further, the motor's residual voltage starts decreasing, and the relative phase angle between the motor voltage and the supply voltage starts increasing. After a certain time the motor has slowed such that the motor residual voltage is out of phase with respect to the supply-bus voltage. Upon reconnection, the starting inrush current could be two times the normal starting inrush current of the motor, which is about 6 to 10 times the rated full load current under the transient conditions and 9 to 15 times the rated full load current under the subtransient conditions. Since the force to which the motor is subject is proportional to the square of the current, such forces could loosen the stator coils, loosen the rotor bars of the induction motors, twist a shaft, or even rip the machine from its base plate. The cumulative abnormal magnetic stresses and/or mechanical shock in the motor windings and to the shaft and couplings could ultimately lead to premature motor failure due to fatigue.

2.5.4 Low-Voltage Magnetic Contactors Typical Wiring (for up to 600 V)

Two basic wiring configurations for controlling a starter or contactor are the two-wire control and the three wire control. Two wire control devices rely primarily on

maintained-contact control circuit devices. That is, the contactors or other device are physically or mechanically held closed to keep the starter coil energized. When this happens, there is always a complete current path in the starter coil circuit. If a voltage failure occurs, the power circuit opens, but when the electricity is restored, the starter picks up immediately and starts the motor. This arrangement might be dangerous, especially if there is a possibility of having people in the area, who assume that the machine has merely been shut off when suddenly power resumes.

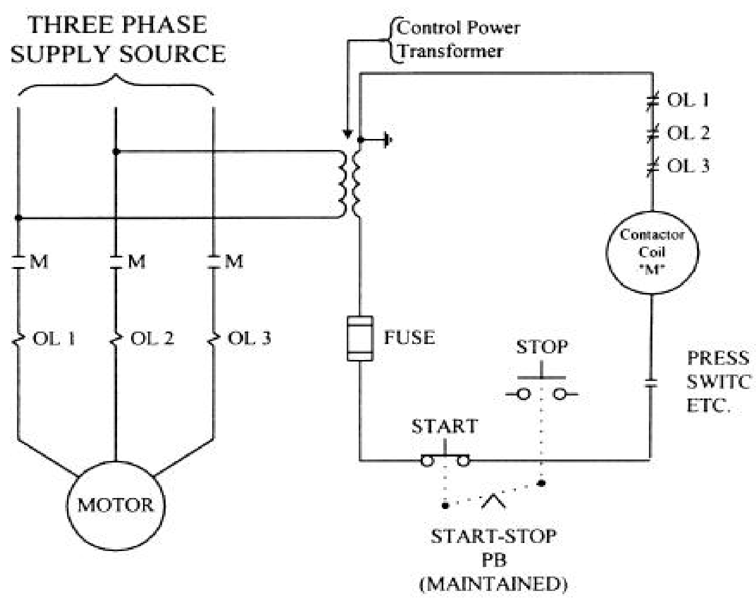

Fig. 2.11 Two wire control circuit, manually held START and STOP

Three wire control schemes provide low voltage protection by utilizing momentary-contact control circuit devices and an auxiliary contact called a holding-circuit interlock. This contact, which is physically located on the starter, operates simultaneously with the power contacts and is wired parallel with the normal open start button in the coil circuit. When the momentary-start button is depressed, current flows through the normally closed stop button, the start button being held closed, the coil, the

overload fuse shown in Fig 2.10 and back to close the control loop. The starter magnet operates and loses all its contacts, including the holding-circuit interlock. Releasing the start button will not deenergize the starter since there is still a closed current path in the control circuit through the stop button, through the holding-circuit interlock, through the coil, through the fuse and back to close the loop.

Three wire control configurations are very safe because they provide low-voltage protection. Under normal circumstances the power contacts close, and the motor runs. If a power failure occurs, the coil will be deenergized and the armature falls away from the magnet. This action releases the control circuit and opens the power contacts to shut off the motor. When power resumes, the starter or contactor coil in a three wire configuration will not be immediately energized because there are no closed current paths to the coil. The momentary-start button is in the open position and the holding-circuit interlock has opened with the release of the coil. There cannot be a closed current path to the starter coil until the start button is again depressed. This prevents accidental start-up by providing low voltage protection, and possible equipment damage.

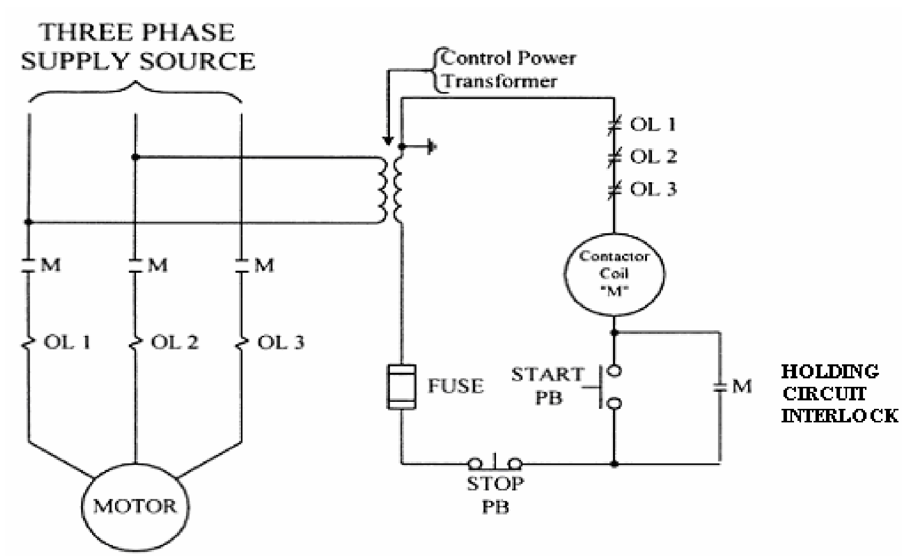

Fig. 2.12 Three wire control circuit

In summary, magnetic motor starters basic functions are to start, stop and protect the motor. Major advantages of using them include:

- They are available in a wider variety of sizes with capacities of up to 1600 HP
- They are capable of frequent switching with a very long life span.
- They can be mounted directly to the machine or remotely.
- They are overall the most versatile motor control devices available, designed to meet practically any motor application.

2.6 Tools

The main tools used in this thesis work were two in particular: ASPEN ONELINER (Advanced Systems for Power Engineering software) created by the ASPEN Company and a DOBLE F-6150 power system simulator. Several motor contactors of different sizes were used in the voltage dip test.

2.6.1 ASPEN Oneliner

ASPEN ONELINER is a PC-based short circuit and relay coordination program for relay engineers. The engineer can change the relay settings and network configuration and see the results of the change immediately. It helps in the accurate modeling of the actual relay, whereas develop the settings took a substantial amount of time, with ASPEN takes a few days.

ASPEN can accurately model 2- and 3-winding transformers, phase shifters, lines, switches, series capacitors and reactors, dc lines, generators, loads, shunts and zero-sequence mutual coupling. ASPEN can provide a detailed modeling of fuses, reclosers, and overcurrent and distance relays. ASPEN has a built-in short circuit program that

simulates all classical fault types: bus faults, line-end, line-out and intermediate faults), as well as simultaneous faults.

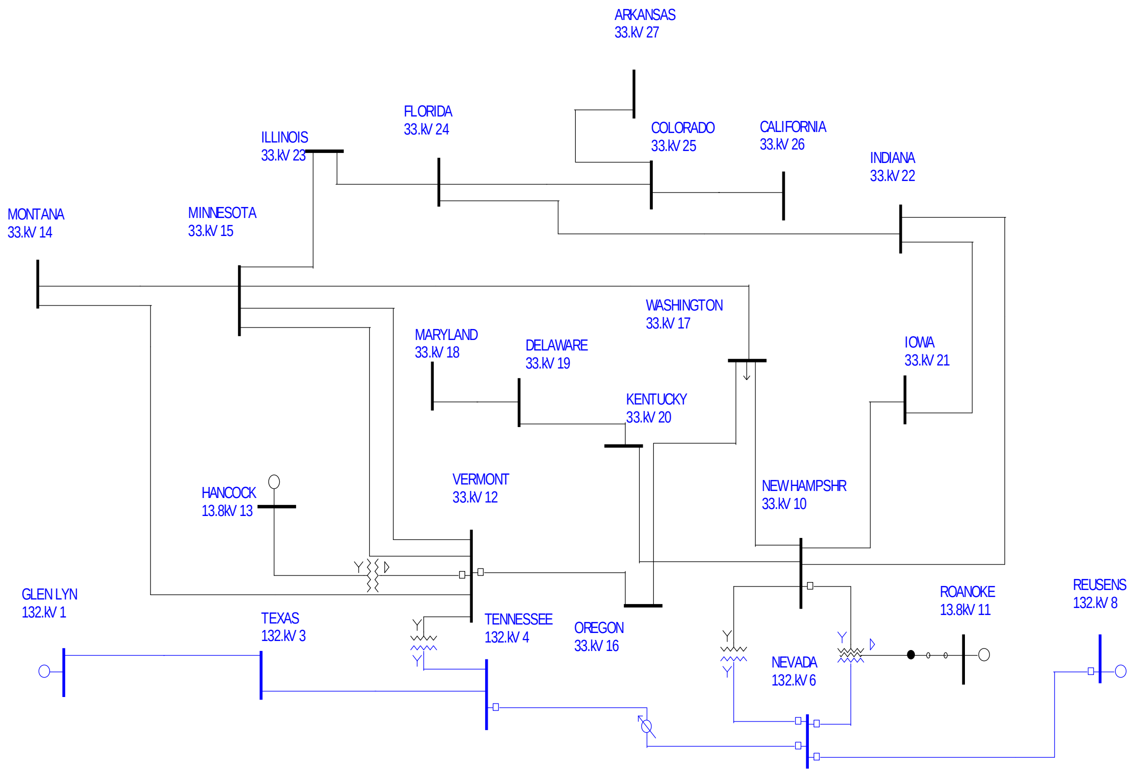

Fig. 2.13 ASPEN ONELINER representation of the American Electric Grid

2.6.2 F-6150 DOBLE Test Set

The F6150 is the only instrument with the high three phase power and adequate software to run full simulation tests on relays and protection schemes. It can test everything from a single, high-burden electromechanical earth/ground fault relay to complete, modern, multi-function numerical microprocessor protection schemes, without the need for additional instruments. It can perform steady-state, dynamic-state, and transient simulation tests. The F-6150 can even be used for end-to-end protection

schemes tests using Global Positioning System technology to synchronize remotely located F-6150s .

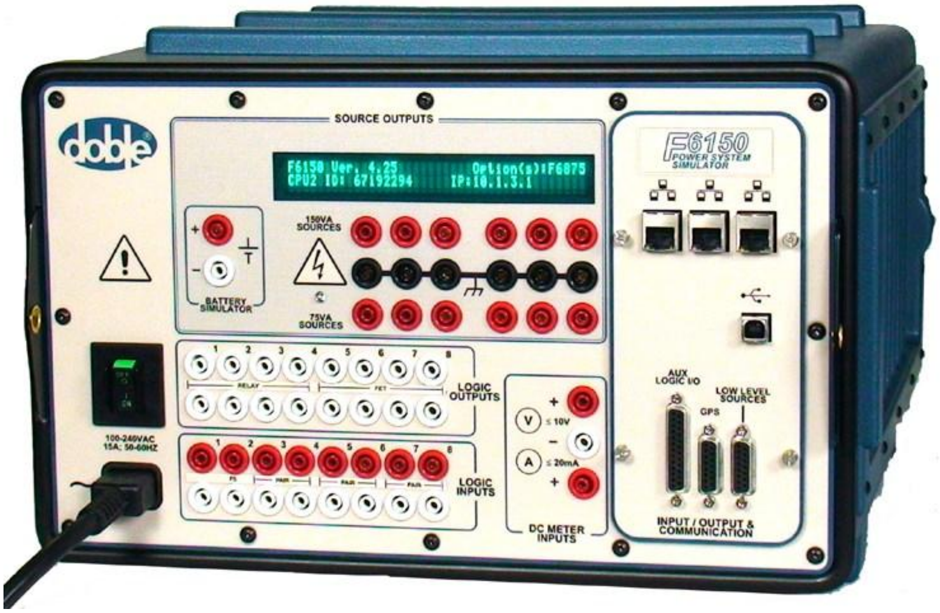

Fig. 2.14 DOBLE F-6150 POWER SYSTEM SIMULATOR

2.7 Protective Relaying Development

The first part of this thesis was to present the advantages for an adaptive transmission relaying protection and how they can protect and mitigate the effects of voltage dips in the transmission system from getting to the low voltage motor controllers downstream.

In the next chapter, this thesis demonstrates the concept and development of a POTT (Direct Transfer Trip) scheme, in which protection settings are based on an adaptive zone acceleration protection, this approach will be proven to be very successful in solving the main goal and problem presented of voltage dips mitigation.

The model of a typical simplified three bus power system and al possible configuration changes are analyzed. Next, a fault study is conducted through multiple sets of situation, types of faults and fault locations.

Then, the results form the fault study were use to determine the correct settings for the relays. Finally, the motor contactors were tested for different types of voltage dips and voltage drop duration to prove how our fast relay clearing times will avoid these controllers from dropping motors out.

CHAPTER 3: DEVELOPMENT OF THE ADAPTIVE PROTECTION SCHEME

3.1 Introduction

This Chapter presents the details of the development of a POTT-DTT (Permissive Over Reaching Transfer Trip-Direct Transfer Trip) for Station A in the network below, using mirror bits over fiber optics, adaptive relay protection for a typical two bus 138 KV system to show the development of all the zones of protection and the value of all the relay element functions available in the SEL-421 [14]. The particular network parameters are presented and the system modeling used in ASPEN. The fault studies and reach calculations were the next steps for the relay setting calculations, several philosophies for these calculations will be used, but they are not necessarily the only philosophies available. The complete relay settings actually loaded to the relay are presented in Appendix A.

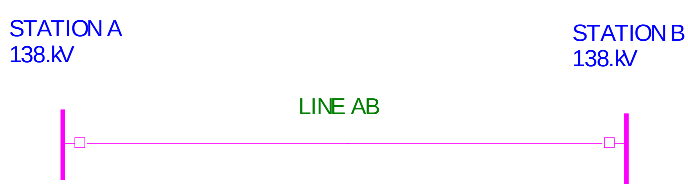

Fig. 3.1 ASPEN two-bus system

3.2 System Modeling

The POTT-DTT scheme using mirror bits over fiber optics will require. For purposes of overreaching zones, to include several lines beyond the next station on both sides. These lines will be included in the fault study and the reach calculations. ASPEN uses subtransient impedance values for the generators in the system, providing the worst

case scenario before the fault currents contribution to the system from the generators starts to decay. The parameters of the whole system are shown in Table 3.1

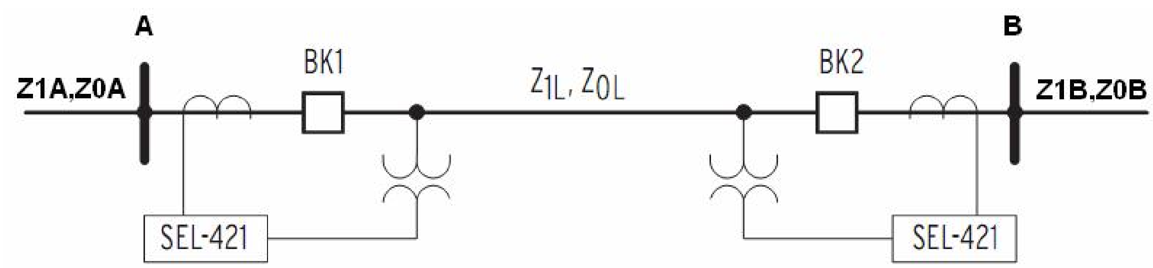

Fig. 3.2 Two bus system protected by two SEL-421 [3] on each terminal station

Table 3.1 138 KV two-bus power system data

PARAMETER	VALUE
NOMINAL SYSTEM LINE-TO-LINE VOLTAGE	138 KV
MVA BASE	100 MVA
NOMINAL FREQUENCY	60 HZ
PTR	1200/5
CTR	2000/5
PHASE ROTATION	ABC
LINE MAXIMUN LOADING	1180 amps
SOURCE A IMPEDANCES:	
Z1A	3.19 ∟84.37 ohms
Z0A	4.60∟80.29 ohms
SOURCE B IMPEDANCES	
Z1B	4.15 ∟84 ohms
Z0B	7.22 ∟79.70 ohms
LINE LENGTH	5 miles
LINE IMPEDANCES:	
Z1L	3.08 ∟81.7 ohms
Z0L	9.41 ∟76.6 ohms

Although our main concern is Line AB, in order to calculate some reaches and adjust some settings in the relay we have to take a bigger picture of the system that is being attempted to protect. Consequently, more lines and consideration come into play which will be explained in further detail in this chapter. All the line and system parameter for the whole system can be found in Appendix B.

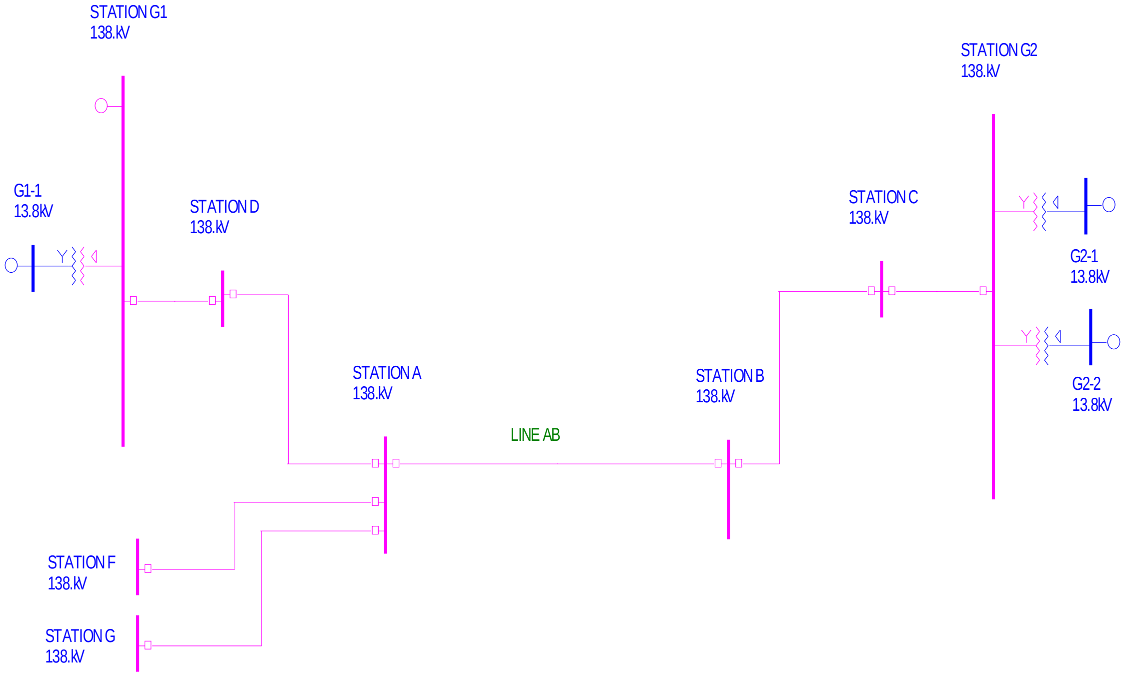

Fig. 3.3 ASPEN screenshot of complete system

3.3 Zone Protection Development

The next step in the development process will be to calculate the reaches of the different zones of protection. The first zone of protection Zone 1 Z1 should be set at 80% of the first line, in this case Line AB:

$$\textbf{Z\_line} = Z_1 L \times Z_{BASE} \times \frac{CTR}{PTR} \quad (3.1)$$

$$\textbf{Z\_line} = (0.00233 + j0.01601) \times 190 \times 0.3333 = 1.0246 \angle\ 81.72 \quad (3.2)$$

$$\textbf{Z1 Reach} = (\%line \times Z_1L = 0.8197 \angle\ 81.72 \quad \textbf{ohm sec} \qquad (3.3)$$

The next zone of protection Zone 2 (Z2) setting must cover 100% of the line and provide coverage beyond the end of the line. For this calculation we will cover 20% of the next shortest line as well. This zone will ensure 100% coverage of the protected line at the receipt of the trip permit from the other end the relay will confirm the presence of an internal fault inside the protected area Line AB.

$$\textbf{Z2 Min Reach} = \%\_line \times Z_1L \times \frac{CTR}{PTR} \qquad (3.4)$$

$$\textbf{Z2 Min Reach} = 120\% \times 3.0739 \times 0.3333 = 1.2296 \angle\ 81.72\ \textbf{ohm sec}$$

For Z3 calculation, first a 3-Phase fault simulation is needed to get the maximum amount of infeed leaving Line AB onto the second line Line BC. From this simulation results, the IFR (Infeed Ratio), is obtained and plugged into the calculation, where Z3 will be set to 120 % of Z1L + (Z1-LineBC x IFR).

This way, the reach calculation will be compensated for the effects of the infeed and it will protect the relay from a misoperation due to apparent impedance, impedance to fault seen by the distance relay which can be different from the actual impedance because of current infeed at some point between the relay and the fault, problems that might see the fault closer or further than it really is.

The maximum load limit of the line will also be taken into consideration and used for the load encroachment setting, relay feature that prevents operation of the phase distance elements during heavy loading.

$$\textbf{Infeed Ratio} = \frac{AMPS\_1st\_LINE\_PU}{AMPS\_2nd\_LINE\_PU}$$

$$\textbf{Infeed Ratio} = \frac{25.26}{25.27} = 0.9996$$

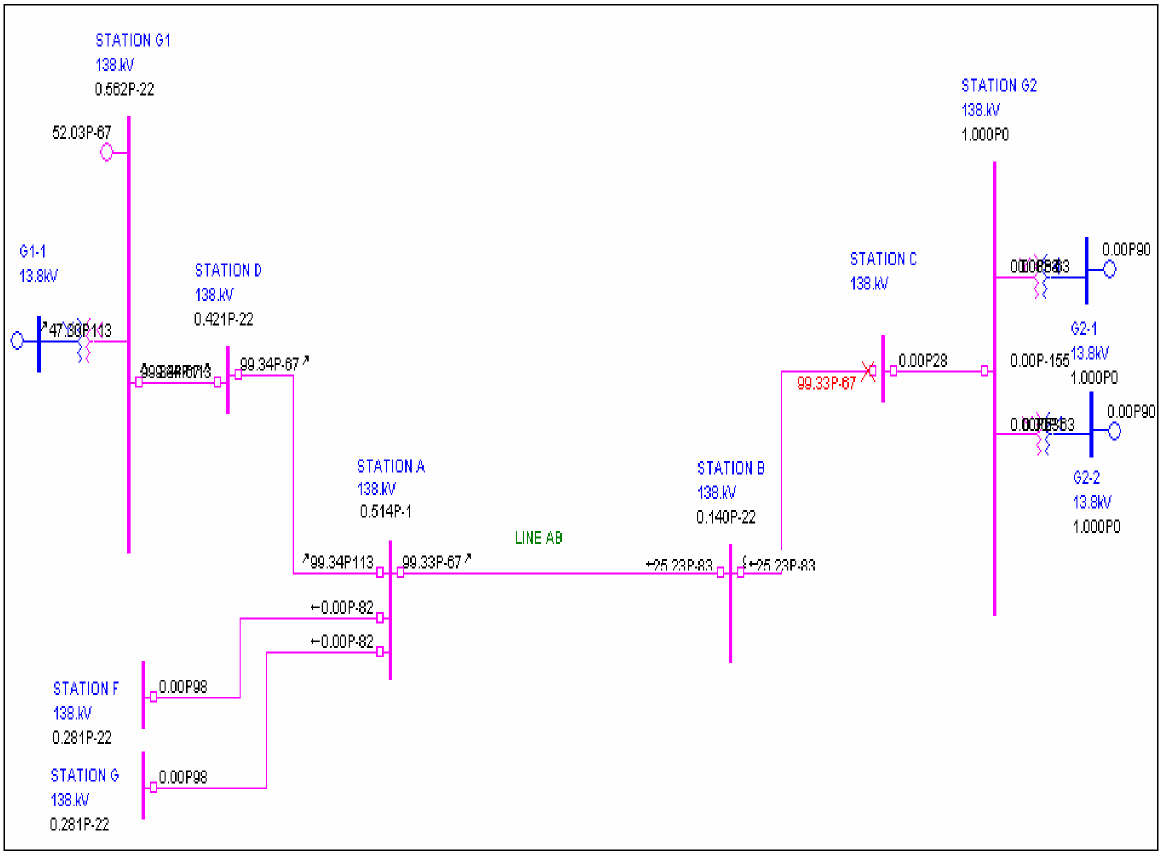

Fig. 3.4 IFR fault study

With the IFR value, Z3 forward can be calculated as follows:

$$\mathbf{Z_3} = \frac{(\%\_line \times (Z_1 L) + (Infeed\_ratio \times Z_1 BC))}{} \qquad (3.7)$$

$$\mathbf{Z_{3\ FORWARD}} = \left(Z3 + \left(Z_{BASE} \times \frac{CTR}{PTR}\right)\right) = 1.5457 \angle 81.58 \textbf{ ohm sec} \qquad (3.8)$$

3.4 Overcurrent Protection Development

The main purpose for the overcurrent protection or fault detectors is to supervise the zone protection in case of a fault very close to the relay terminal in the system. This fault will cause the voltage to drop almost instantaneously to zero, preventing the relay from operating. The next step in the development of the relay settings entails the fault detector calculations for terminal Station A looking at Line AB, using different types of fault.

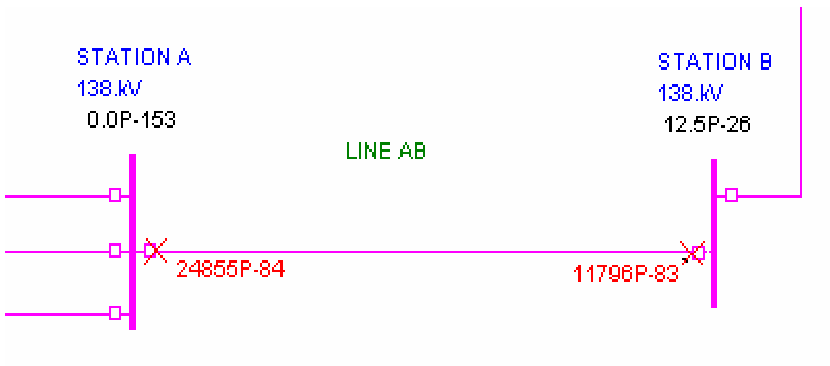

Fig. 3.5 Fault current difference between a close fault and a fault at the end of the line, voltage at bus A goes to zero.

In figure 3.2 the effect of a close fault and a remote fault are presented, the amount of fault current is almost double, a tremendous amount of fault current will immediately set the alarm to trip even if the distance elements fail to operate.

Faults are simulated in ASPEN, in combination with a single contingency situation, in this case, placing out of service the line behind terminal STATION A, Line AD, given the fact that is the strongest source and it is the worst case scenario. The fault current values will be used later on to calculate the phase fault detector settings, and the time-overcurrent and instantaneous settings.

Table 3.2 Fault current simulation from Aspen

Fault Currents Calculations			
Fault type: ===>	3LG	L-L	1LG
Line End Fault (All Sources In = maximum Fault available)	11,808	8,519	8,409
Remote Bus Fault (All Sources In) Used for instantaneous calculation.	19,184	12,835	15,388
Remote Bus Fault (Strongest Source Removed)	4,002	3,466	4,029
Line End Fault (Strongest Source Removed)	4,478	3,878	3,864
2nd Longest Line, Line End Fault (Strongest Source Removed) 51GP			3,604

Once the fault currents calculation are available, the next step is to obtain, the X/R ratio must be obtained from ASPEN and the SIR ratio for 3 phase faults must be derived in order to provide maximum security once relay has started Zone 1 operation. This ensures that the Zone 1 will not overreach during an external fault.

When a fault occurs, DC offset may be present as a result of the requirements that no instantaneous change of current can incur in an inductance, and that the current must lag the voltage by the natural power factor of the system. The DC offset decays with a time constant equal to the X/R ratio of the system supplying the fault. This X/R ratio is also entered as a constant in the relay, and it will automatically adjust to compensate for it [1].

Another consideration that has to be made in this section is the Source-to-line (SIR) impedance ratio. This ratio can be high due to low line impedance (short lines), weak sources behind the line or a combination of both. A high SIR leads to low voltages at the relay location, and it might also lead to lower currents if the high ratio is caused by

a stronger source and low line impedance. These two reasons might affect the speed and the reach of the relays that is why they have to be included in the relay setting in order to compensate for it.

The X/R ratio is obtained by simulation a close in 3 phase close in fault, providing the maximum amount of fault current available

Table 3.3 X/R ratio from ASPEN

X/R = 9.56237			
R1	**X1**	**R0**	**X0**
0.38135	3.64660	0.93949	5.47609

Then, the SIR for Zone 1 phase faults and ZG for Z1 ground faults is the next step:

$$\textbf{SIR} = \frac{(Z_1\,SourceA\_\mathrm{Im}\,pedance)}{\%\_line\_\mathrm{cov}ered} \times Z_1\,LineAB \times Z_{BASE} \qquad (3.9)$$

$$\textbf{SIR} = \frac{(0.381 + \mathrm{j}3.6466)}{80\%} \times 0.00233 + j0.01601 \times 190 = 1.49095 \qquad (3.10)$$

$$\mathbf{Z_{GSmax}} = \frac{(2 \times (Z_1 A) + (Z_0 A))}{3} \qquad (3.11)$$

$$\mathbf{Z_{GSmax}} = \frac{(2 \times (0.38135 + j3.6466) + (0.939 + j5.47609))}{3} = 4.29408 \angle 82.41 \ \textbf{ohm} \qquad (3.12)$$

$$\mathbf{Z_{G}} = \frac{(\%\_line\_\mathrm{cov}ered \times [2 \times ((Z_1 A) + (Z_0 A))])}{3} \qquad (3.13)$$

$$Z_G = \frac{(80\% \times [2 \times ((0.00233 + j0.01601) + (0.01146 + j0.04806))])}{3} \qquad (3.14)$$

$$Z_G = 4.13878 \angle 78.62 \quad \textbf{ohm} \qquad (3.15)$$

Having $\mathbf{Z_G}$ and $\mathbf{Z_{GSmax}}$, then $\mathbf{SIR_{GE}}$ is obtained, this value will be the ground SIR for Line AB, and its function is to ensure proper relay operation for Zone 1 trips.

$$\mathbf{SIR_{GE}} = \frac{(Z_{GS\,MAX})}{Z_G} = 4.29408 / 4.13878 = 1.03752 \qquad (3.16)$$

Once the SIR ratios for both line and ground distance elements have been calculated, the next step in the settings development is to calculate the fault detector settings for the overcurrent elements in the relay.

First the load and line limits for all zones of protection except Zone 1, and then, the instantaneous overcurrent setting for Zone 1. The Zone 1 setting has to be

Table 3.4 Load limits Z2-Z3

Load Limit for all zones but Zone 1			
Line limit	**1180**	A	primary
Check line limit at:	**125**	%	of line rating
Breaker Rating (Maximum Load)	**1200**	A	primary
Check breaker limit at:	**115**	%	of breaker rating

The calculation of the forward phase to phase load current settings is going to provide the relay with the tools to differentiate between fault current and maximum load current. It will also set the relay elements to look in the forward direction while the relay takes care of the direction calculation. The discussion of direction elements is not in the scope of the thesis.

Maximum load limit = $\frac{\left(sqrt(3)\times \max load \times \lim it\right)}{CTR}$ (3.17)

Maximum load limit cuurent = $\frac{\left(1.732\times 1200\times 1.15\right)}{400}$ = **5.98 A** phase-phase load (3.18)

Line limit current = $\frac{\left(sqrt(3)\times Line\_\lim it \times Assumed\_Max\_\lim it\right)}{CTR}$ = **6.39 A** (3.19)

Phase-to-phase forward limit = 6.39 A

Table 3.5 Load limits Zone 1

Zone 1: And 87LPP				
Minimum 3-phase fault	=	**4002**	A	primary
Minimum phase-phase fault		**3466**	A	primary
% of min. multi-phase fault.	=	**80**	%	

FWD Z1(based on 3 Phase fault) = $\frac{\left(sqrt(3)\times Fault\_primary\_amps \times \% fault\right)}{CTR}$ (3.20)

FWD Z1(based on 3 Phase fault) = $\frac{\left(1.73\times 4002\times 0.8\right)}{400}$ = 13.86 A (3.21)

Line limit (max line load) = $\frac{\left(sqrt(3)\times Line \lim it \times \%load\_125\%\right)}{CTR}$ (3.22)

Line limit (max line load) = $\frac{\left(1.7332\times 1180\times 1.25\right)}{CTR}$ = 6.39 A (Ph_Ph load) (3.23)

The final calculation steps in the settings development involve the Loss of Potential LOP) computation setting and the ground time-overcurrent and instantaneous settings.

This Loss of potential setting will also supervise the trip condition for an unexpected situation like loss of voltage from the substation or an opened breaker.

$$\textbf{LOP Overcurrent (115\% CT rating)} = \frac{(Factor\_115\% \times CT\_rating)}{CTR} \quad (3.24)$$

LOP Overcurrent (115% CT rating) = 5.75

3.5 Relay Settings

Finally, the adaptive protection relaying is ready to be entered in the microprocessor relay; the following steps are the final consideration to be made regarding the communication aided POTT scheme. The objective of this chapter is not to explore in detail every setting in the relay, just present the overall tripping logic.

First, the, **ECOMM: =** POTT, communications-aided assisted trip should be selected to start the application; this step will tell the relay the scheme to be use. Next we set our zones of protection, three zones of phase (mho characteristics calculated previously) Zone 1, forward looking instantaneous underreaching, Zone 2 forward looking, communications-assisted and time delayed tripping and Zone 3 forward zones that prevent unwanted tripping during external faults.

The General global settings for the SEL-421 [14] contain all the line parameters at Station A will be applied as follows:

Table 3.6 Global Settings

Global		
Setting	**Range**	**Value**
SID: Station Identifier (40 characters)	Range = ASCII string with a maximum length of 40.	**STATION A**
RID: Relay Identifier (40 characters)	Range = ASCII string with a maximum length of 40.	LINE AB
NUMBK Number of Breakers in Scheme	Select: 1, 2	1
BID1: Breaker 1 Identifier (40 characters)	Range = ASCII string with a maximum length of 40.	BRK 1
NFREQ Nominal System Frequency	Select: 50, 60	60

The relay configuration is then set, starting with the magnitude of Line AB positive and zero sequence, then all the zones of protection, both phase and ground calculated in the previous section, for complete settings see Appendix A

Table 3.7 Line AB settings

Group 1	Line Parameters	
Setting	**Range**	**Value**
Z1MAG: Pos.-Seq. Line Impedance Magnitude	Range = 0.05 to 255.00	1.02
Z1ANG Pos.-Seq. Line Impedance Angle	Range = 5.00 to 90.00	81.8
Z0MAG: Zero-Seq. Line Impedance Magnitude	Range = 0.05 to 255.00	3.13
Z0ANG: Zero-Seq. Line Impedance Angle	Range = 5.00 to 90.00	76.6
LL Line Length	Range = 0.10 to 999.00	4.84
ELOP Loss-of-Potential	Select: Yes,No	Y

The magnitudes and the time delays for each zone of protection are shown in Table 3.8, the setting OFF means that is not being used.

Table 3.8 Zone1-Zone 3 settings

Group 1		
Setting	**Range**	**Value**
Z1P Zone 1 Reach	Range = 0.05 to 64.00, OFF	0.81
Z2P Zone 2 Reach	Range = 0.05 to 64.00, OFF	1.23
Z3P Zone 3 Reach	Range = 0.05 to 64.00, OFF	5.15
Z4P Zone 4 Reach	Range = 0.05 to 64.00, OFF	OFF

The corresponding time delays for the protected zones are presented below:

Table 3.9 Zone-time delay settings

Group 1		
Setting	**Range**	**Value**
Z1PD Zone 1 Time Delay	Range = 0.000 to 16000.000, OFF	OFF
Z2PD Zone 2 Time Delay	Range = 0.000 to 16000.000, OFF	20 cycles
Z3PD Zone 3 Time Delay	Range = 0.000 to 16000.000, OFF	50 cycles

The permissive overreaching transfer trip will provide high speed tripping for faults along the protected line. It consists of two sections:

- Echo (Breaker opened and Loss of Communication monitoring)
- Permission to Trip Received

If the local circuit breaker is open and if communications are being sent and received in a normal fashion between the local and the remote terminal are out, the relay can issue an echo back to the remote relay through the TMB2A mirror bit, the

term will be explained below. In the first case, if the remote breaker is opened, it will cause it to issue a high-speed trip for fault beyond the remote terminal Zone 1 reach. In the second case it can cause the Zone 2 reach of the relay to delay for a few cycles waiting for the closer relays to trip. In the application for this thesis a 10 cycle delay will be used

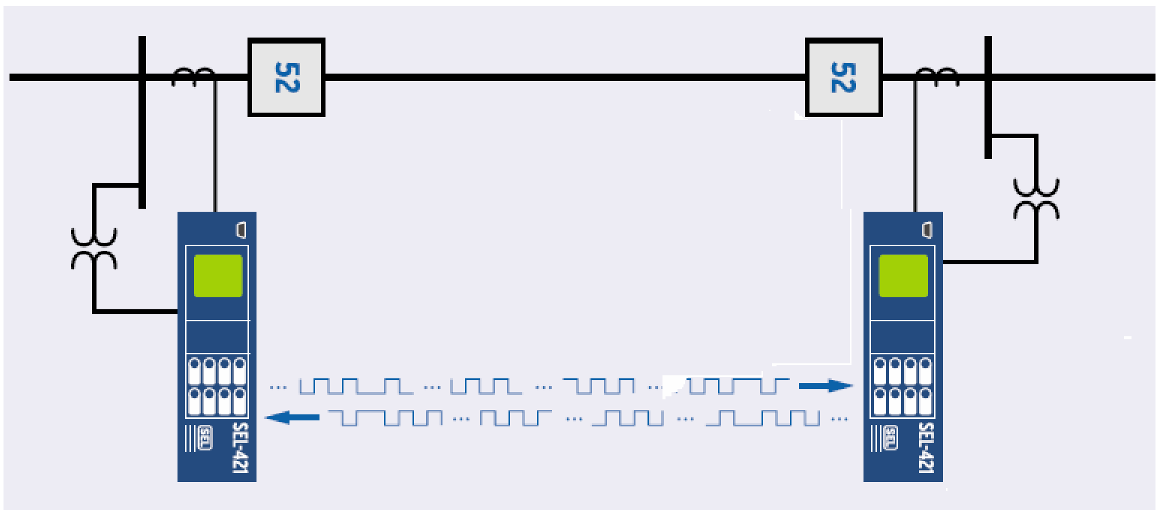

Figure 3.6 POTT communication scheme requires constant communication between both relays

The SEL Mirror bit technology is a relay to relay communication technology that does not require any other device, relays can be connected directly simply by using a dual fiber optic link for the SEND and RECEIVE channels.

Table 3.10 Mirror-bits definitions

Transfer Mirror Bits:	
TMB1A:	Trip
TMB2A:	Echo sent
Receive Mirror Bits:	
RMB1A:	Remote Relay trip
RMB2A:	Remote echo received

Finally, the trip condition of the POTT scheme is set in the relay, if **RMB1A**: is received from the other end, the relay can high speed trip for internal faults inside the protected area, if **TMB1A** is asserted, the relay will delay the Zone 2 operation until it receives another permit establishing that the line is closed.

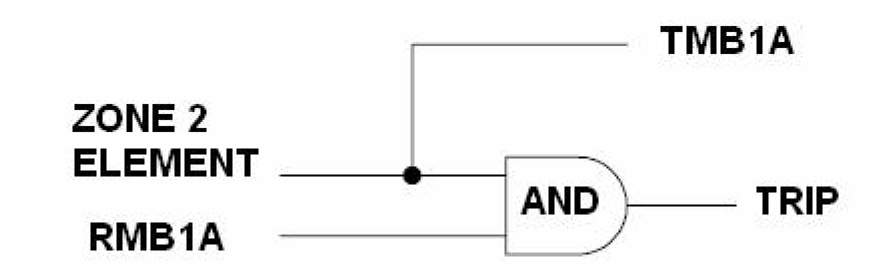

Figure 3.7 POTT basic logic

Finally, the trip logic is configured in the device, the settings consists in a two main forms of TRIP equations: one **TR** (Unrestricted Trip), decision made internally independently of communication status, and the other is the **TRCOMM** (communications-assisted) which will speed up the unrestricted trip and the Zone 2 trip providing very high speed action.

Table 3.11 Trip equations

TR Trip	Zone 1 or Zone 2 or Trip received	Z1P OR (Z2P\Z2PD) OR (Z3P\Z3PD) OR TMB1A
TRCOMM Communication Aided Trip	Trip	M2P

CHAPTER 4: MOTOR CONTACTOR PERFOMANCE TEST

4.1 Introduction

This Chapter presents the performance test of different 480V motor contactors sizes, and an actual industrial induction motor. The experiment was based on the concept that the rated control voltage of 120 V for these contactors started to cause them to drop the motors out around 0.5 PU voltages depending on the duration of the fault event. Several tests were made with two different contactors of two different sizes, for multiple fault durations. Dropout time VS voltage graph is plotted to simulate the loss of control voltage for short circuit faults at the bus and starting from the bus to the transmission system.

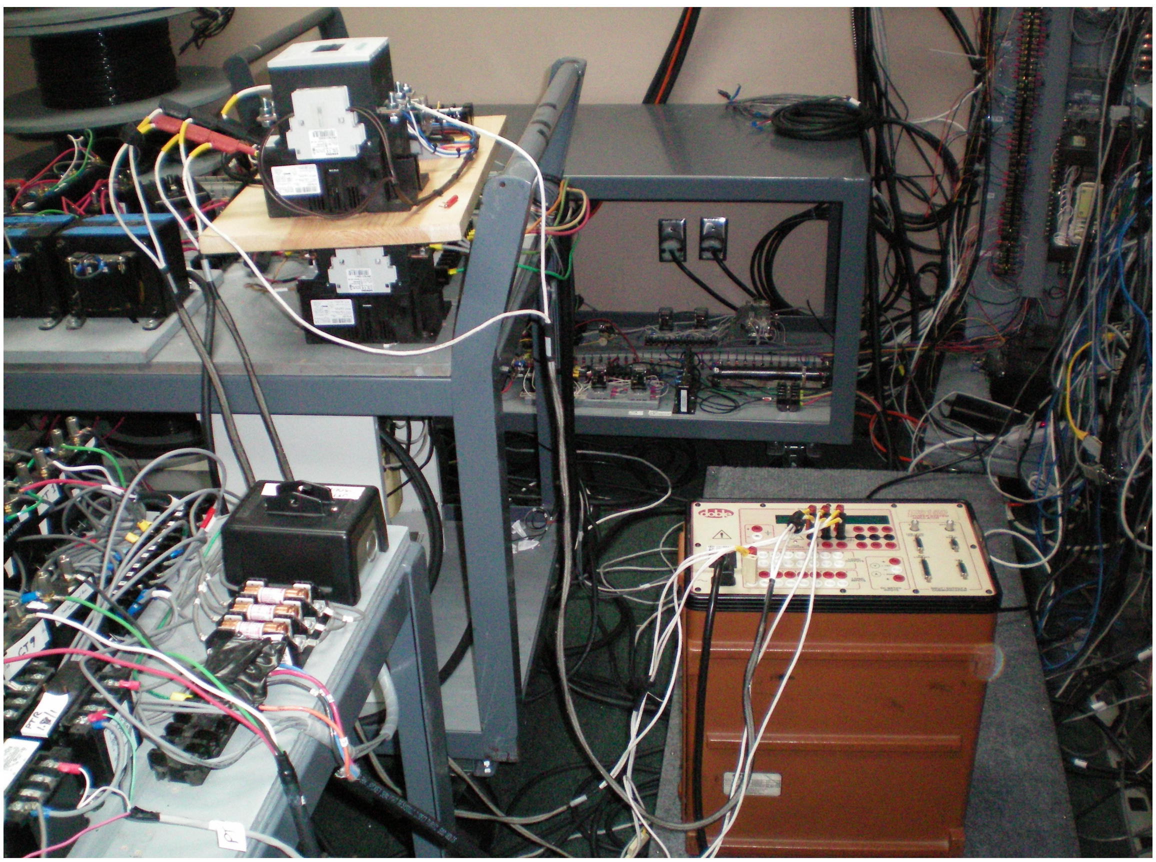

Fig. 4.1 Test setup, DOBLE test set powering the motor controller

4.2 Test Setup

The experiment was conducted using the DOBLE F-6150 power system simulator to replicate the control voltage from the power system to the motor contactors in the controller and simulate all types of faults in the system. The open → close contact in the motor controller was also wired to the DOBLE test set to record and register the time when the motor drops out and opens the three phase connections.

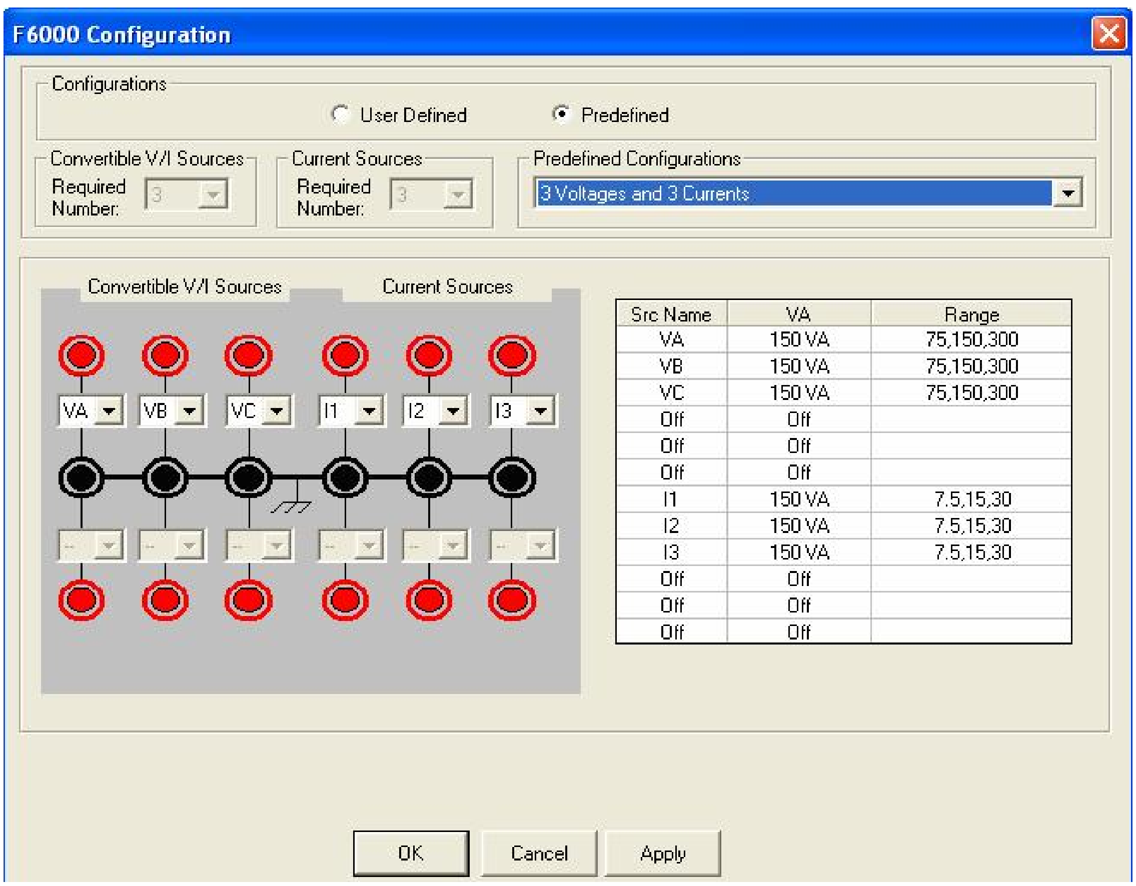

Fig. 4.2 Output configuration for the DOBLE simulator

From Figure 4.2, the wiring on the front of the DOBLE is shown; the test required a 120 V source since both contactors tested are rated at 120 V. The motor controlled in the experiment is shown in Figure 4.3, a Dayton Electric, 3 HP, 200 Volt motor.

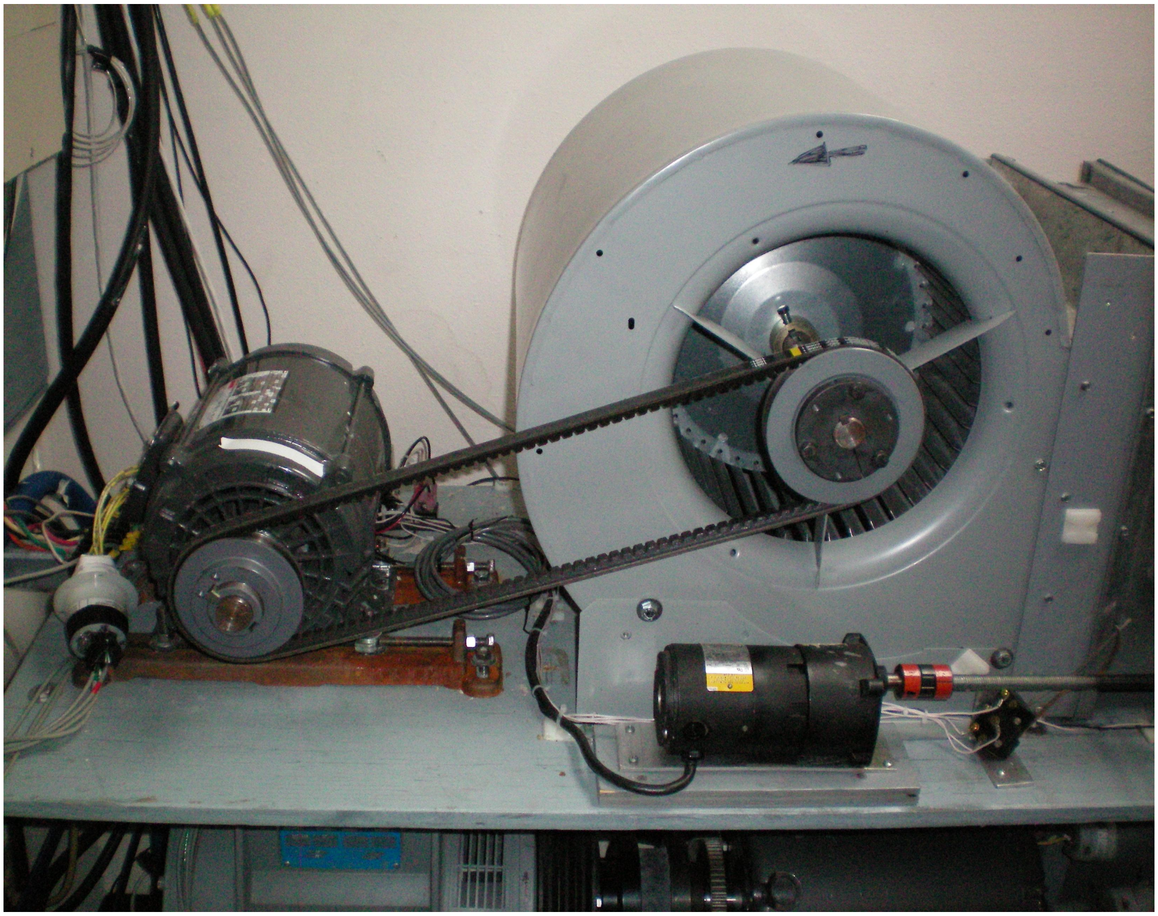

Fig. 4.3 200-Volt motor used in the performance test.

4.3 Performance Tests

The results from the performance test have two basic parts, the results for a motor controller with a NEMA size 1 contactor and the results for the motor controller with a NEMA size 3 contactor. For the first test, the motor controller was subjected to different voltages during a 120 cycle window (2 seconds).

The first results f or the size 1 contactor are shown in Figure 4.5, the test included several 2 second duration short circuit faults with different voltages:

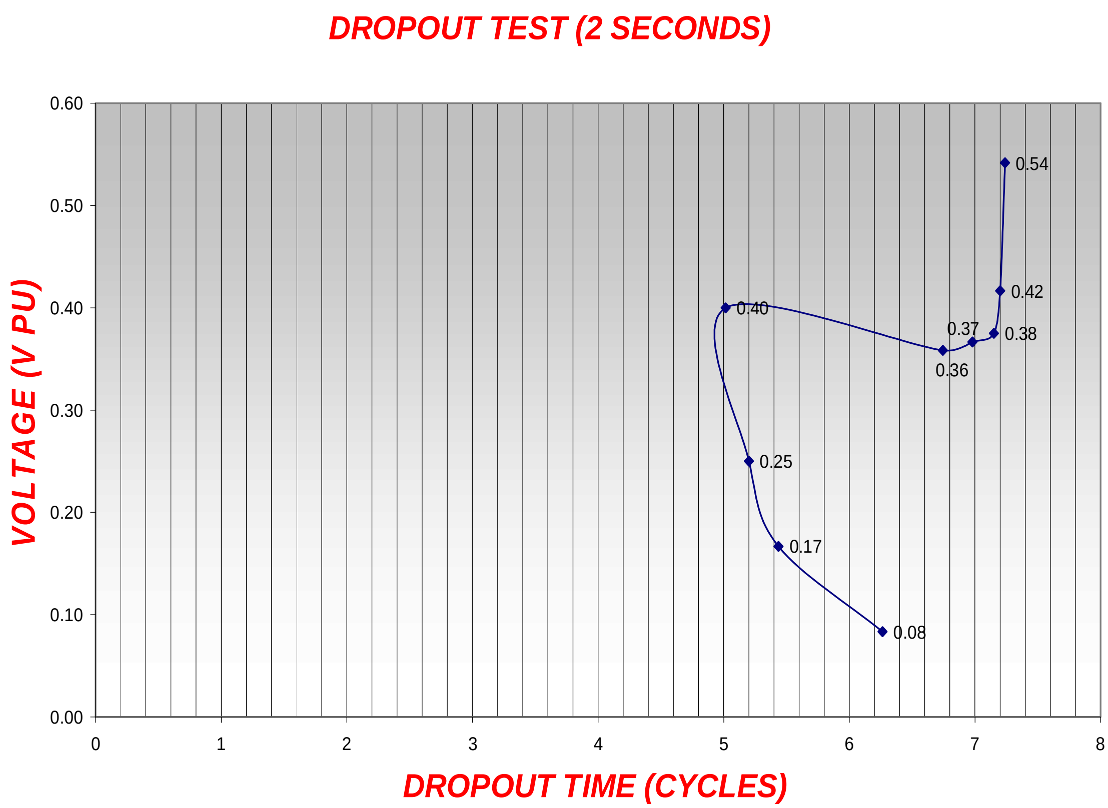

Fig. 4.4 Dropout test for Allen Bradley NEMA size 1 contactor.

Figure 4.4 shows how the motor controller starts to dropout between 70 and 60 volts, approximately 0.54 PU. We ran several iterations to avoid any random errors in the readings. It is also appreciable form the graph that the dropout time at about 0.54 PU is approximately 7.2 cycles.

The realistic drop in voltage form a short circuit fault in the system will cause the motors to shut down, the relay protection will operate before this time window preventing this situating of escalating consequences.

Figure 4.5 shows a controller with a NEMA size 3 contactor subjected to the same variation of control voltage during 2 seconds intervals.

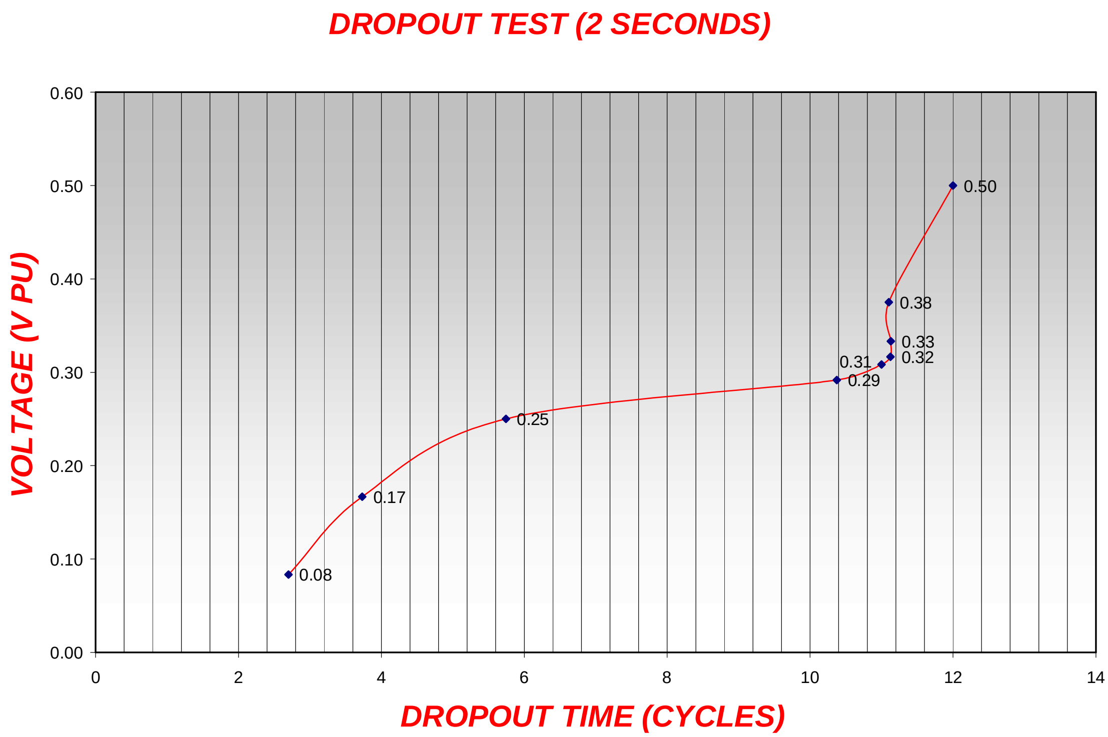

Fig. 4.5 Dropout test for Siemens Sirius NEMA size 3 contactor.

Figure 4.5 shows how the controller starts to drop the motor out between 60 and 50 volts, approximately 0.5 PU at approximately 12 cycles.

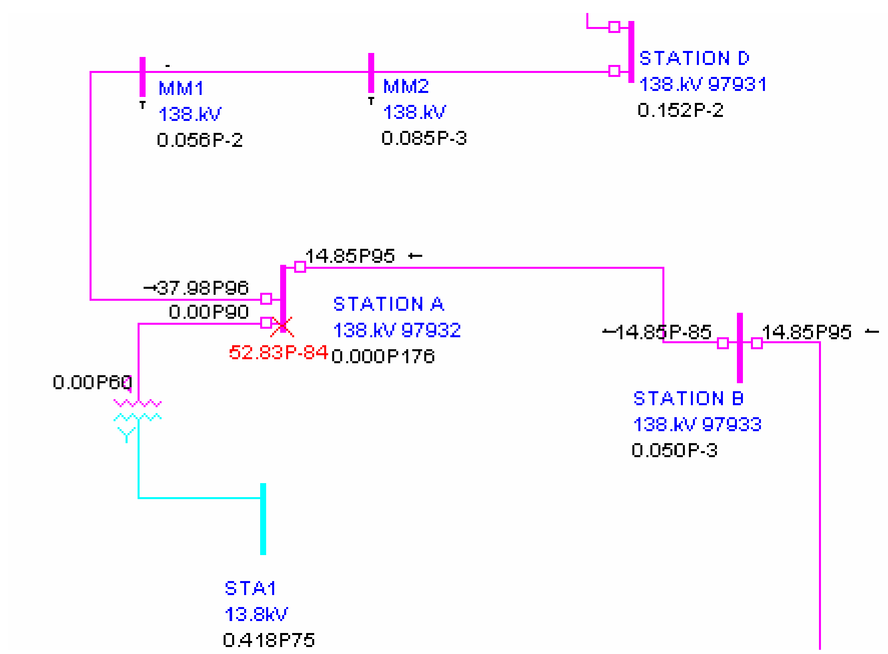

Fig. 4.6 ASPEN simulated 3-phase fault at Station A

The next step involved a comparison between the voltage drop in the system running ASPEN simulations and the obtained voltage drop from the live tests. First, simulations for 3-phase faults at the next bus and the second next bus are presented below:

Table 4.1 ASPEN 3 phase fault simulations at bus

13.8 KV BUS STA1 VOLTAGE (PU)	BUS FAULT LOCATION
0.418	STATION A
0.496	STATION B
0.505	STATION C
0.534	STATION D

Then, a comprehensive simulation of 3-phase faults every 10% of the line from Station A to Stations B and D was conducted as well, considering that the scope of this thesis is not to study the effect of voltage stability or transient stability beyond the reaches of the protective relay scheme; hence no more locations were included.

Table 4.2 ASPEN 3 phase fault simulations at Line AB

13.8 KV BUS STA1 VOLTAGE (PU)	LINE FAULT LOCATON (% DISTANCE)
FROM STATION A TO STATION B	
0.43	10
0.436	20
0.45	30
0.459	50
0.47	60
0.481	70
0.490	80
0.496	90

Table 4.3 ASPEN 3 phase fault simulations at Line AD

13.8 KV BUS STA1 VOLTAGE (PU)	LINE FAULT LOCATON (% DISTANCE)
FROM STATION A TO STATION D	
0.43	10
0.444	20
0.456	30
0.459	50
0.478	60
0.484	70
0.495	80
0.505	90

All voltages in the results are in stated in the per unit system, the visualization of the voltage drop results will be much easier having the same reference for the low and the high side.

A very important assumption had to be taken into consideration for this project was since this project focused on very low voltage motors we assumed there was no backfeed from the motor. In really big motors with ratings of hundred or even thousands of horsepower, the motor controller will be able to ride through a voltage dip much easier than a small one, thanks to the inertia of the motor that will sustain the voltage and hold the fast decay in voltage for a certain period of time.

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

The goal of this thesis was to prove that an adaptive relay protection in the transmission system could clear a specific fault caused by a transitory event, events that occur very frequently in the transmission system. The results show that for a worst case scenario, a 3 -Phase fault in the 138 KV bus at Station A, the voltage will drop so low that the motor contactor will drop out at 0.5 or 0.4 PU. According to the results from the contactor tests, for the Size 1 contactor, it would drop at 6.2 cycles and for the size 3 at 2.7 cycles. If we move along the transmission line we notice that the POTT scheme will clear all faults before 4 or 5 cycles, ensuring that the contactors will not drop the motors out. The Zone 1 and the almost instantaneous Zone 2 thanks to the communication aided trip will provide 100% protection for the line and a worst case scenario, a bus fault at Station A.

Once again, power system protection proves to be extremely critical in order to keep the power system running, and not only the high voltage power system, but all the associated loads and customer downstream.

This work can provide a base for future studies on different types of adaptive protections and on different kinds of motor controllers. The use of the DOBLE test set simplified the task of subjecting the motor controller to all these different situations. In the future, perhaps different kinds of power systems and the real backfeed from the motors can be added to the study.

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APPENDIX-A: SETTING FILES

Table A.1. 2.11 Complete relay settings with all available elements

SETTINGS SHEET		
Line:	LINE AB	
Breaker(s):	BK1	
Group 1		
Setting	Range	Value
CTRW Current Transformer Ratio - Input W	Range = 1 to 50000	400
CTRX Current Transformer Ratio - Input X	Range = 1 to 50000	400
PTRY Potential Transformer Ratio - Input Y	Range = 1 to 10000	1200
VNOMY PT Nominal Voltage (L-L) - Input Y	Range = 60 to 300	115
PTRZ Potential Transformer Ratio - Input Z	Range = 1 to 10000	700
VNOMZ PT Nominal Voltage (L-L) - Input Z	Range = 60 to 300	197
Z1MAG Pos.-Seq. Line Impedance Magnitude	Range = 0.05 to 255.00	1.02
Z1ANG Pos.-Seq. Line Impedance Angle	Range = 5.00 to 90.00	81.8
Z0MAG Zero-Seq. Line Impedance Magnitude	Range = 0.05 to 255.00	3.13
Z0ANG Zero-Seq. Line Impedance Angle	Range = 5.00 to 90.00	76.6
LL Line Length	Range = 0.10 to 999.00	4.84
EFLOC Fault Location	Select: Y, N	Y
E21P Mho Phase Distance Zones	Select: N, 1-5	5
E21MG Mho Ground Distance Zones	Select: N, 1-5	5
E21XG Quadrilateral Ground Distance Zones	Select: N, 1-5	1
ECVT Transient Detection	Select: Y, N	Y
ESERCMP Series-Compensated Line Logic	Select: Y, N	N
ECDTD Distance Element Common TD	Select: Y, N	Y
ESOTF Switch-Onto-Fault	Select: Y, N	Y
EOOS Out-of-Step	Select: Y, N	N
ELOAD Load Encroachment	Select: Y, N	Y

E50P Phase Inst./Def.-Time O/C Elements	Select: N, 1-4	3
E50G Res. Ground Inst./Def.-Time O/C Elements	Select: N, 1-4	3
E50Q Neg.-Seq. Inst./Def.-Time O/C Elements	Select: N, 1-4	3
E51S Selectable Inverse-Time O/C Elements	Select: N, 1-3	1
E32 Directional Control	Select: Y, AUTO	AUTO
ECOMM Comm. Scheme	Select: N, DCB, POTT, POTT2, POTT3, DCUB1, DCUB2	POTT
EBFL1 Breaker 1 Failure Logic	Select: N, 1, 2	1
E25BK1 Synchronism Check for Breaker 1	Select: Y, N	Y
E79 Reclosing	Select: Y, Y1, N	N
EMANCL Manual Closing	Select: Y, N	Y
ELOP Loss-of-Potential	Select: Y, Y1, N	Y1
EDEM Demand Metering	Select: N, THM, ROL	THM
EADVS Advanced Settings	Select: Y, N	N
Z1P Zone 1 Reach	Range = 0.05 to 64.00, OFF	0.81
Z2P Zone 2 Reach	Range = 0.05 to 64.00, OFF	1.23
Z3P Zone 3 Reach	Range = 0.05 to 64.00, OFF	5.15
Z4P Zone 4 Reach	Range = 0.05 to 64.00, OFF	1.55
Z5P Zone 5 Reach	Range = 0.05 to 64.00, OFF	2.05
Z1PD Zone 1 Time Delay	Range = 0.000 to 16000.000, OFF	OFF
Z2PD Zone 2 Time Delay	Range = 0.000 to 16000.000, OFF	OFF
Z3PD Zone 3 Time Delay	Range = 0.000 to 16000.000, OFF	OFF
Z4PD Zone 4 Time Delay	Range = 0.000 to 16000.000, OFF	50
Z5PD Zone 5 Time Delay	Range = 0.000 to 16000.000, OFF	OFF
Z1MG Zone 1	Range = 0.05 to 64.00, OFF	0.81
Z2MG Zone 2	Range = 0.05 to 64.00, OFF	1.23
Z3MG Zone 3	Range = 0.05 to 64.00, OFF	5.15

Z4MG Zone 4	Range = 0.05 to 64.00, OFF	1.55
Z5MG Zone 5	Range = 0.05 to 64.00, OFF	2.05
XG1 Zone 1 Reactance	Range = 0.05 to 64.00, OFF	0.81
RG1 Zone 1 Resistance	Range = 0.05 to 50.00	4.05
Z1GD Zone 1 Time Delay	Range = 0.000 to 16000.000, OFF	OFF
Z2GD Zone 2 Time Delay	Range = 0.000 to 16000.000, OFF	OFF
Z3GD Zone 3 Time Delay	Range = 0.000 to 16000.000, OFF	OFF
Z4GD Zone 4 Time Delay	Range = 0.000 to 16000.000, OFF	50
Z5GD Zone 5 Time Delay	Range = 0.000 to 16000.000, OFF	OFF
k0M1 Zone 1 ZSC Factor Magnitude	Range = 0.000 to 10.000, AUTO	0.687
k0A1 Zone 1 ZSC Factor Angle	Range = -180.00 to 180.00	-7.6
Z1D Zone 1 Time Delay	Range = 0.000 to 16000.000, OFF	0
Z2D Zone 2 Time Delay	Range = 0.000 to 16000.000, OFF	OFF
Z3D Zone 3 Time Delay	Range = 0.000 to 16000.000, OFF	OFF
Z4D Zone 4 Time Delay	Range = 0.000 to 16000.000, OFF	30
Z5D Zone 5 Time Delay	Range = 0.000 to 16000.000, OFF	OFF
ESPSTF Single-Pole Switch-Onto-Fault	Select: Y, N	N
EVRST Switch-Onto-Fault Voltage Reset	Select: Y, N	N
52AEND 52A Pole-Open Time Delay	Range = 0.000 to 16000.000, OFF	10
CLOEND CLSMON or 1 Pole Open Delay	Range = 0.000 to 16000.000, OFF	OFF
SOTFD Switch-Onto-Fault Enable Duration	Range = 0.500 to 16000.000	30
CLSMON Close Signal Monitor	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	NA
ZLF Forward Load Impedance	Range = 0.05 to 64.00	12.75
ZLR Reverse Load Impedance	Range = 0.05 to 64.00	12.75

PLAF Forward Load Positive Angle	Range = -90.0 to 90.0	30
NLAF Forward Load Negative Angle	Range = -90.0 to 90.0	-30
PLAR Reverse Load Positive Angle	Range = 90.0 to 270.0	150
NLAR Reverse Load Negative Angle	Range = 90.0 to 270.0	210
50P1P Level 1 Pickup	Range = 0.25 to 100.00, OFF	7.5
50P2P Level 2 Pickup	Range = 0.25 to 100.00, OFF	5.75
50P3P Level 3 Pickup	Range = 0.25 to 100.00, OFF	12.5
67P1D Level 1 Time Delay	Range = 0.000 to 16000.000	2
67P2D Level 2 Time Delay	Range = 0.000 to 16000.000	0
67P3D Level 3 Time Delay	Range = 0.000 to 16000.000	0
67P1TC Level 1 Torque Control	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	VAFIM < 46 OR VBFIM < 46 OR VCFIM < 46 #SOTF 50 SUPV 70% NOM
67P2TC Level 2 Torque Control	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	1
67P3TC Level 3 Torque Control	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	1
50G1P Level 1 Pickup	Range = 0.25 to 100.00, OFF	OFF
50G2P Level 2 Pickup	Range = 0.25 to 100.00, OFF	2.95
50G3P Level 3 Pickup	Range = 0.25 to 100.00, OFF	0.5
67G2D Level 2 Time Delay	Range = 0.000 to 16000.000	0
67G3D Level 3 Time Delay	Range = 0.000 to 16000.000	0
67G2TC Level 2 Torque Control	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	1
67G3TC Level 3 Torque Control	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	1

50Q1P Level 1 Pickup	Range = 0.25 to 100.00, OFF	OFF
50Q2P Level 2 Pickup	Range = 0.25 to 100.00, OFF	OFF
50Q3P Level 3 Pickup	Range = 0.25 to 100.00, OFF	1
67Q3D Level 3 Time Delay	Range = 0.000 to 16000.000	0
67Q3TC Level 3 Torque Control	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	1
51S1O 51S1 Operating Quantity	Select: IAL, IA1, IA2, IBL, IB1, IB2, ICL, IC1, IC2, ImaxL, Imax1, Imax2, I1L, 3I2L, 3I0L, 3I01, 3I02	3I0L
51S1P 51S1 O/C Pickup	Range = 0.25 to 16.00	1
51S1C 51S1 Inv-Time O/C Curve	Select: U1, U2, U3, U4, U5, C1, C2, C3, C4, C5	U2
51S1TD 51S1 Inv-Time O/C Time Dial	Range = 0.50 to 15.00	5.8
51S1RS 51S1 Inv-Time O/C EM Reset	Select: Y, N	Y
51S1TC 51S1 Torque Control	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	32GF
DIR3 Zone/Level 3 Directional Control	Select: F, R	R
DIR4 Zone/Level 4 Directional Control	Select: F, R	F
DIR5 Zone/Level 5 Directional Control	Select: F, R	F
ORDER Ground Dir. Element Priority (combine Q,V,I)	Select: Q, V, I, any Combination of Q,V and I	QV
E32IV Zero-Seq. Voltage & Current Enable	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	1
EPO Pole Open Detection	Select: 52, V	52
SPOD Single Pole Open Time Dropout Delay	Range = 0.000 to 60.000	0.5
3POD Three Pole Open Time Dropout Delay	Range = 0.000 to 60.000	1.5

Z3RBD Zone 3 Reverse Block Time Delay	Range = 0.000 to 16000.000	6
EBLKD Echo Block Time Delay	Range = 0.000 to 16000.000, OFF	8
ETDPU Echo Time Delay Pickup	Range = 0.000 to 16000.000, OFF	1
EDURD Echo Duration Time Delay	Range = 0.000 to 16000.000	6
EWFC Weak Infeed Trip	Select: Y, N, SP	N
PT1 General Permissive Trip Received	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	(RMB3A OR PB8) AND NOT IN103 # REMOTE KEY OR LOCAL SIMULATION
50FP1 Phase Fault Current Pickup -BK1	Range = 0.50 to 50.00	5.75
BFPU1Breaker Failure Time Delay -BK1	Range = 0.000 to 6000.000	10
RTPU1 Retrip Time Delay -BK1	Range = 0.000 to 6000.000	3
BFI3P1 Three Pole Breaker Failure Init -BK1	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	IN203 AND LCBF1
BFIA1 A-Phase Breaker Failure Init -BK1	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	NA
BFIB1 B-Phase Breaker Failure Init -BK1	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	NA
BFIC1 C-Phase Breaker Failure Init -BK1	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	NA
BFIDO1 Breaker Failure Init Dropout Delay -BK1	Range = 0.000 to 1000.000	1.5
BFISP1 Breaker Failure Init Seal-in Delay -BK1	Range = 0.000 to 1000.000	2
ENCBF1 No Current/Residual Current Logic -BK1	Select: Y, N	Y
50RP1 Residual Current Pickup -BK1	Range = 0.25 to 50.00	1
NPU1 No Current Brkr Failure Delay -BK1	Range = 0.000 to 6000.000	10
BFIN1 No Current Brkr Failure Initiative -BK1	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	50R1

ELCBF1 Load Current Breaker Failure Logic -BK1	Select: Y, N	Y
50LP1 Phase Load Current Pickup -BK1	Range = 0.25 to 50.00	0.25
LCPU1 Load Pickup Time Delay -BK1	Range = 0.000 to 6000.000	0
BFILC1 Breaker Failure Load Current Init -BK1	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	1
EFOBF1 Flashover Breaker Failure Logic -BK1	Select: Y, N	N
BFTR1 Breaker Failure Trip -BK1	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	FBF1 OR NBF1 # PHASE BKR FAILURE OR RESIDUAL BKR FAILURE
BFULTR1 Breaker Failure Unlatch Trip -BK1	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	1 # ALWAYS UNLATCH
SYNCP Synch Reference	Select: VAY, VBY, VCY, VAZ, VBZ, VCZ	VAZ
25VL Voltage Window Low Thresh	Range = 20.0 to 200.0	85
25VH Voltage Window High Thresh	Range = 20.0 to 200.0	142
SYNCS1 Synch Source 1	Select: VAY, VBY, VCY, VAZ, VBZ, VCZ	VBY
KS1M Synch Source 1 Ratio Factor	Range = 0.10 to 3.00	1.71
KS1A Synch Source 1 Angle Shift	Range = 0 to 330	0
25SFBK1 Maximum Slip Frequency -BK1	Range = 0.005 to 0.500, OFF	0.1
ANG1BK1 Maximum Angle Difference 1 -BK1	Range = 3.0 to 80.0	40
ANG2BK1 Maximum Angle Difference 2 -BK1	Range = 3.0 to 80.0	40
TCLSBK1 Breaker 1 Close Time	Range = 1.00 to 30.00	9
BSYNBK1 Block Synchronism Check -BK1	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	52AA1
BKCFD Breaker Close Failure Delay	Range = 1 to 99999, OFF	60

ULCL1 Unlatch Closing for Breaker 1	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	1
BK1MCL Breaker 1 Manual Close	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	0 # NOT USED-EXTERNAL SWITCH
EVCK Reclosing Voltage Check	Select: Y, N	Y
27LP Dead Line Voltage	Range = 1.0 to 200.0	28
59LP Live Line Voltage	Range = 1.0 to 200.0	85
27BK1P Breaker 1 Dead Busbar Voltage	Range = 1.0 to 200.0	28
59BK1P Breaker 1 Live Busbar Voltage	Range = 1.0 to 200.0	85
DMTC Demand Metering Time Constant	Range = 5 to 300	15
PDEMP Phase Current Pickup	Range = 0.50 to 16.00, OFF	OFF
GDEMP Residual Ground Current Pickup	Range = 0.50 to 16.00, OFF	OFF
QDEMP Neg.-Seq. Current Pickup	Range = 0.50 to 16.00, OFF	OFF
TR Trip	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	Z1T OR (M2P OR Z2G) AND Z4T OR M4PT OR Z4GT OR PCT04Q OR PCT14Q OR PCT16Q OR 51S1T AND NOT RB13
TRCOMM Communication Aided Trip	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	(M2P OR Z2G OR PCT01Q) AND NOT IN103
TRSOTF Switch-Onto-Fault Trip	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	M2P OR Z2G OR 67P1T OR 50P3
DTA Direct Transfer Trip A-Phase	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	NA
DTB Direct Transfer Trip B-Phase	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	NA

DTC Direct Transfer Trip C-Phase	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	NA
BK1MTR Breaker 1 Manual Trip	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	0 # NOT USED-EXTERNAL SWITCH
ULTR Unlatch Trip	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	1
ULMTR1 Unlatch Manual Trip -BK1	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	1
TOPD Trip During Open Pole Time Delay	Range = 2.000 to 8000.000	2
TULO Trip Unlatch Option	Select: 1-4	4
Z2GTSP Zone 2 Ground Distance Time Delay SPT	Select: Y, N	N
67QGSP Zone 2 Dir. Neg.-Seq./Res. Overcurrent SPT	Select: Y, N	N
TDUR1D SPT Min Trip Duration Time Delay	Range = 2.000 to 8000.000	4
TDUR3D 3PT Min Trip Duration Time Delay	Range = 2.000 to 8000.000	4
E3PT Three-Pole Trip Enable	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	1
E3PT1 Breaker 1 3PT	Valid range = The legal operators: AND OR NOT R_TRIG F_TRIG	1

APPENDIX-B: ASPEN NETWORK PARAMETER SCREENSHOTS

All the parameters of the elements used in the network are presented as screenshots from ASPEN:

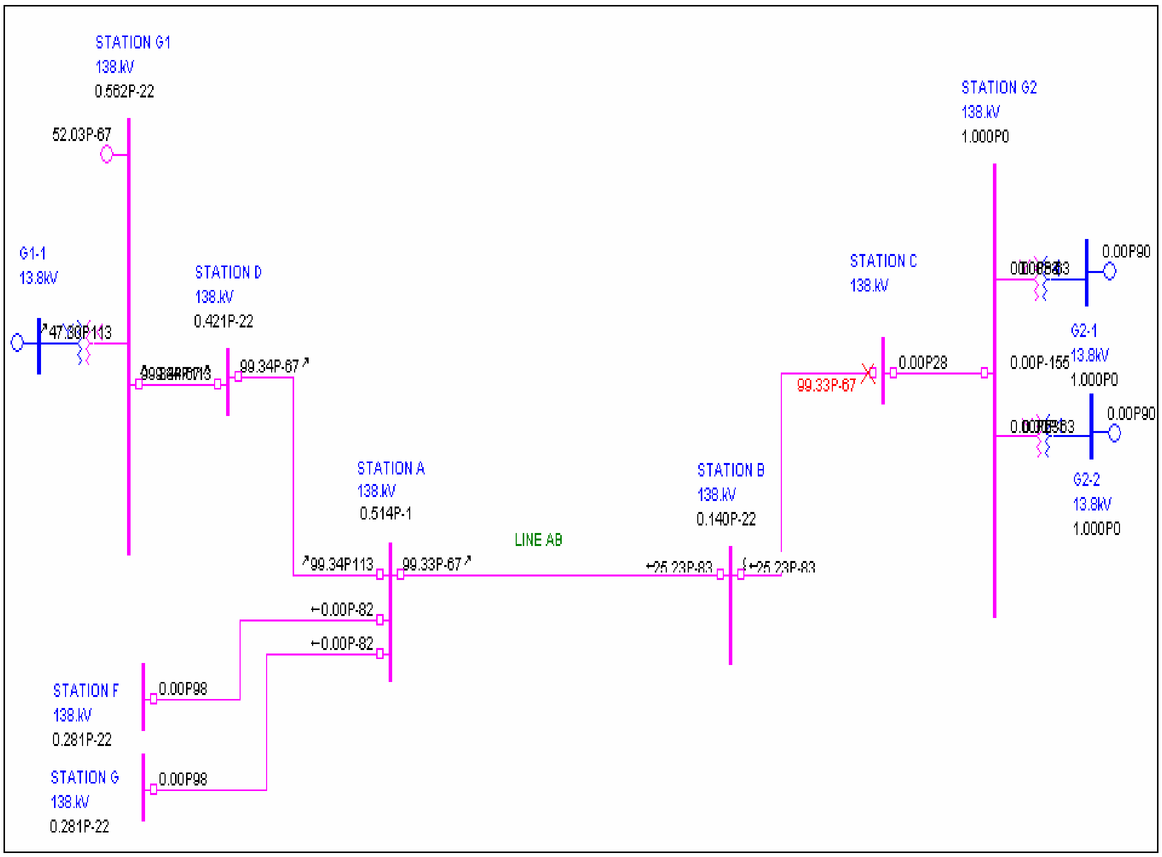

Fig B.1 Complete network

Station G1 equivalent parameters:

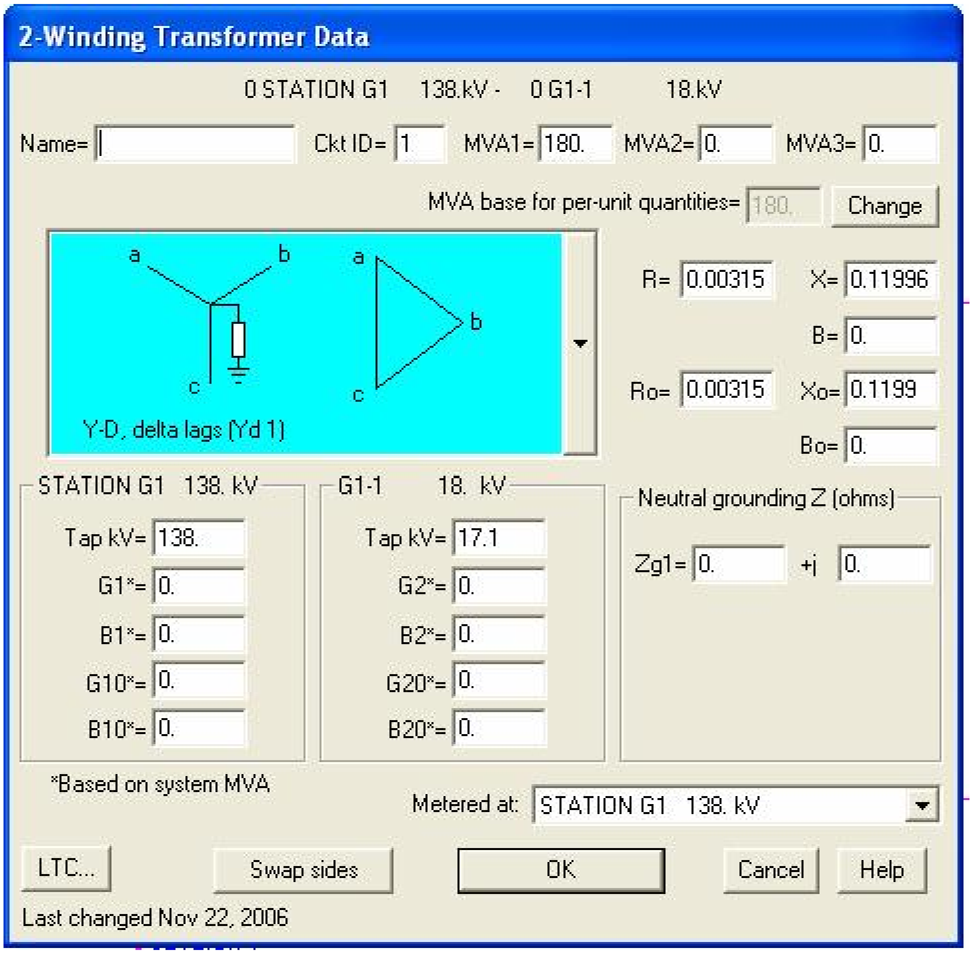

Fig B.2 Station G1- G1-1 transformer parameters

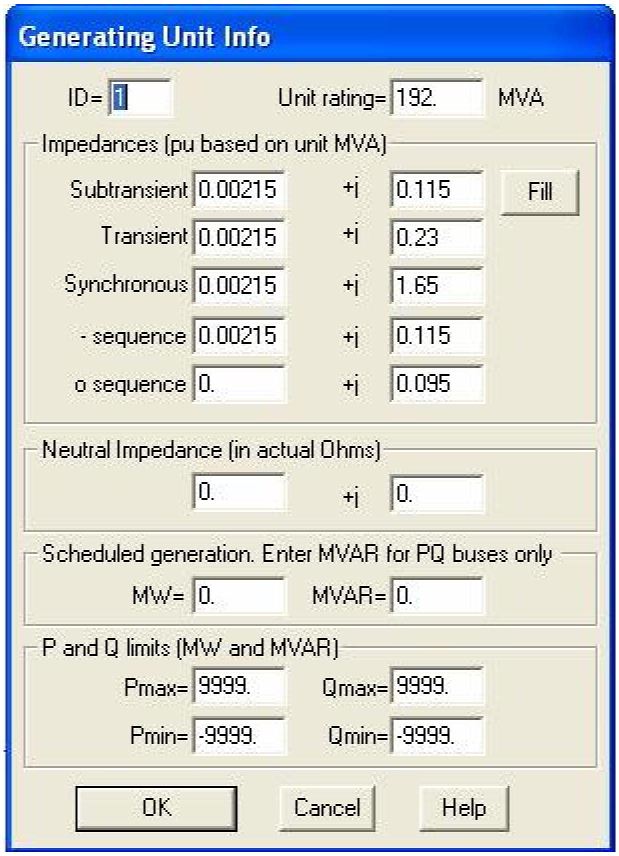

Fig B.3 Station G1-1 generator parameters

Transmission line parameters:

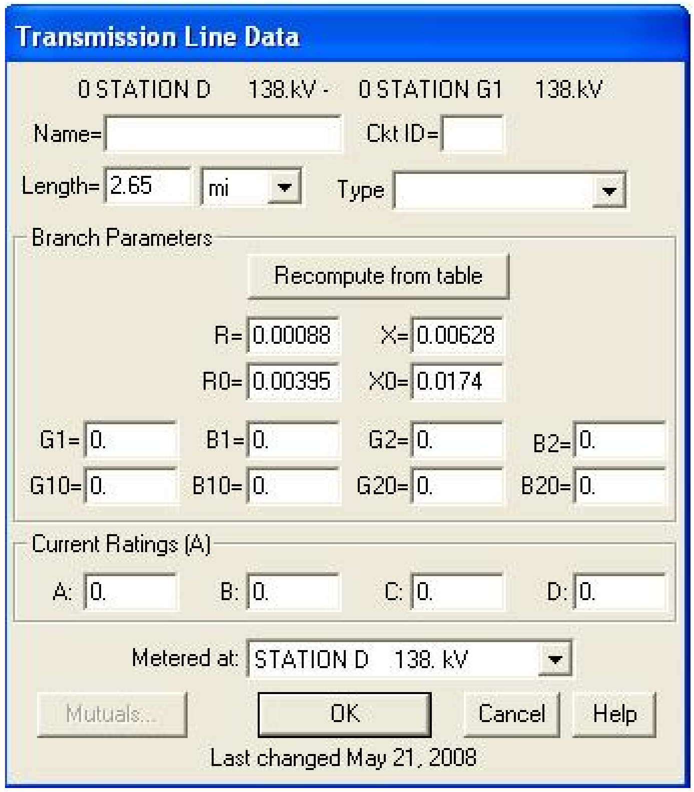

Fig B.4 Station D – Station G1 T-line

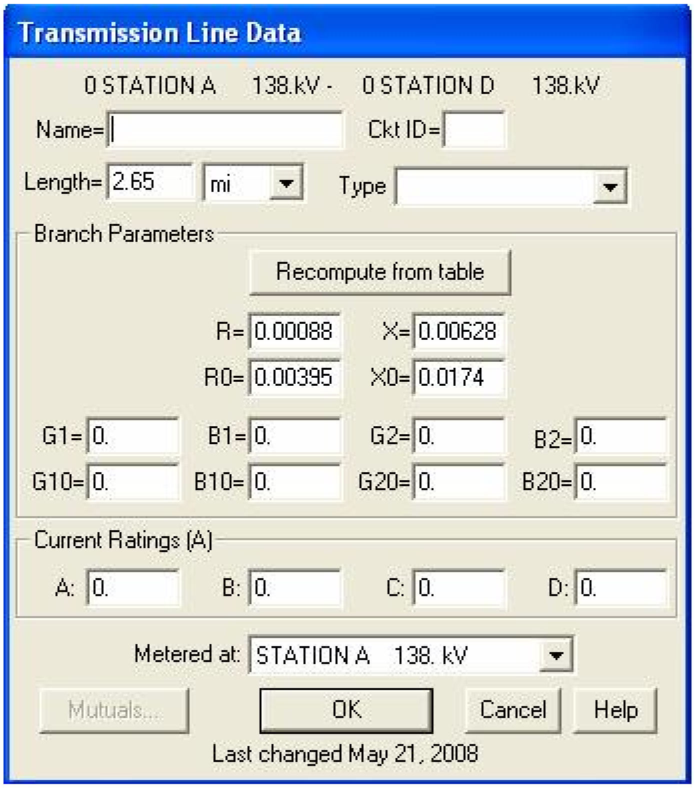

Fig B.5 Station A – Station D T-line

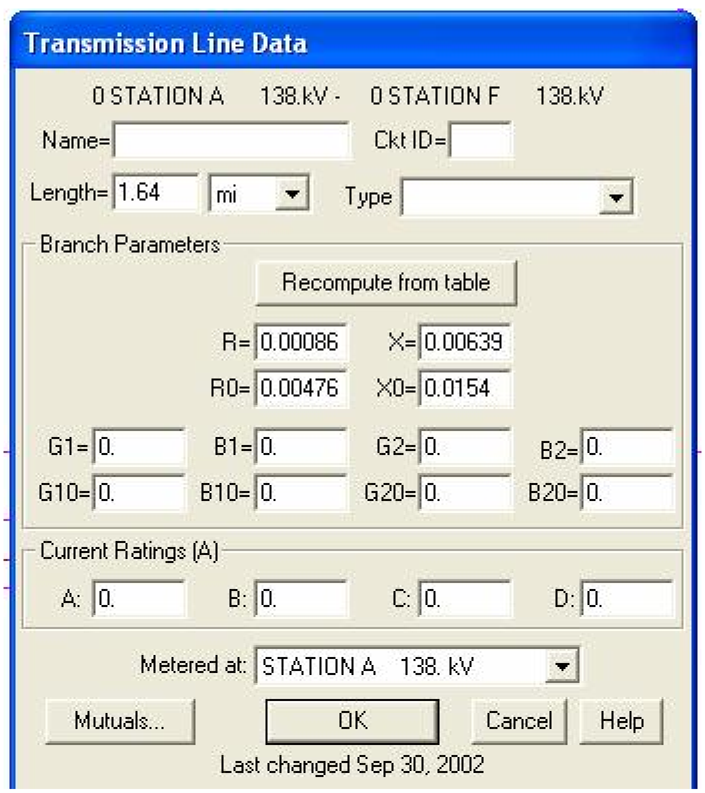

Fig B.6 Station A – Station F T-line

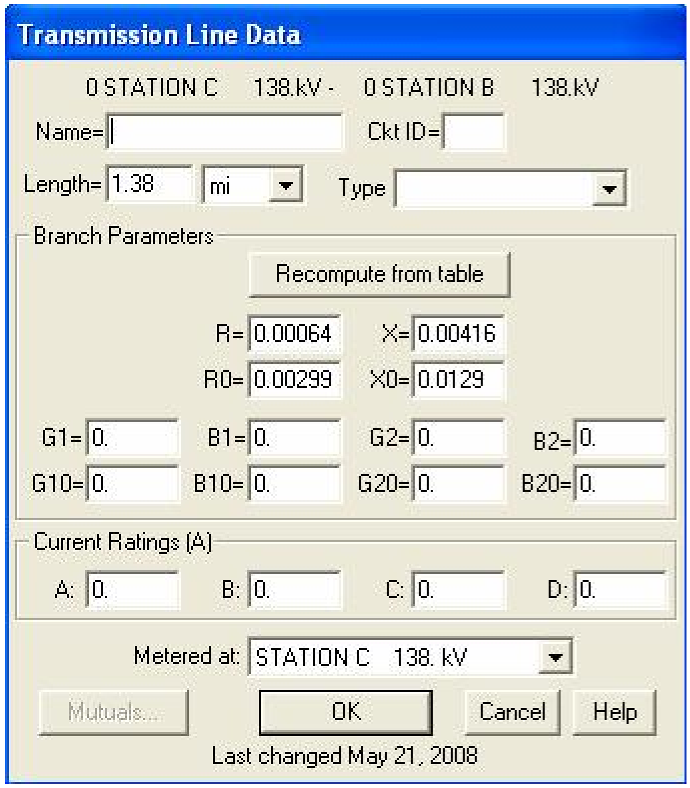

Fig B.7 Station C – Station B T-line

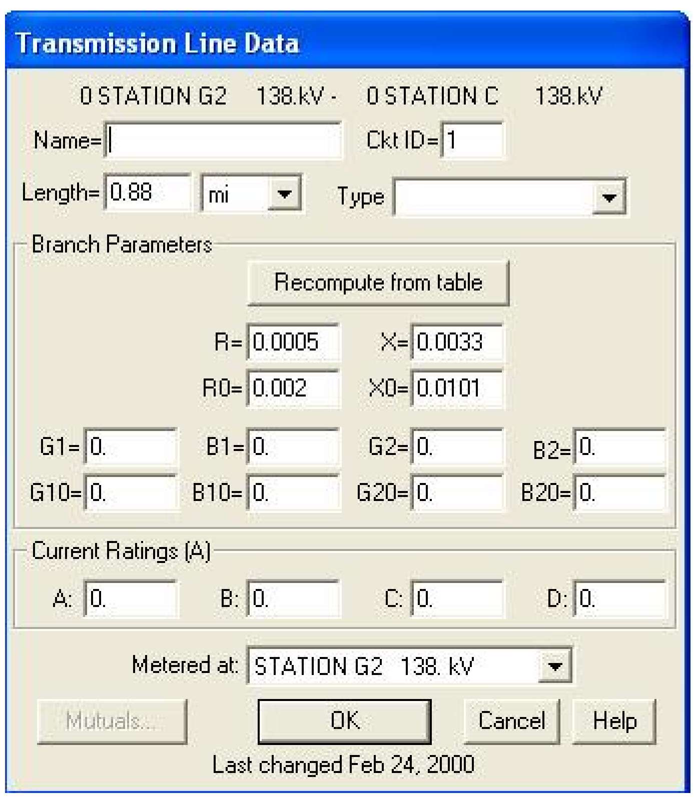

Fig B.8 Station G2 – Station C T-line

Station G2 equivalent parameters:

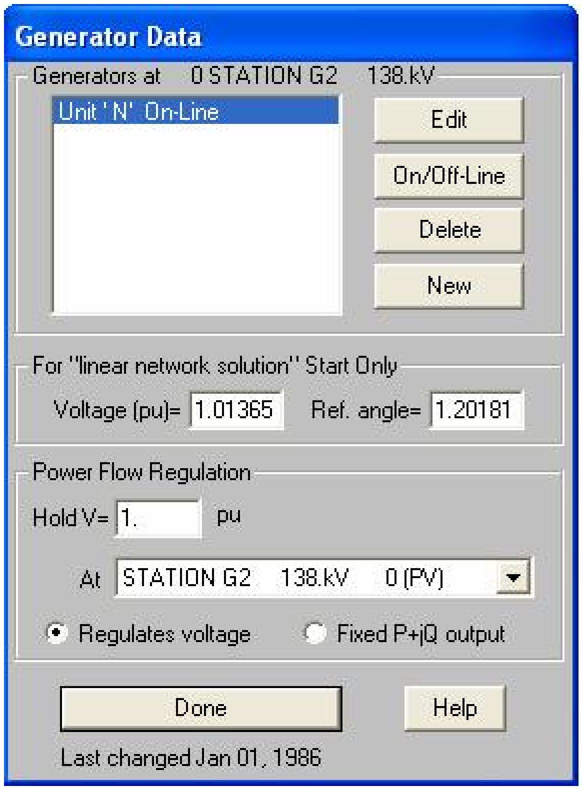

Fig B.9 Generator at G2 equivalent voltage and angle

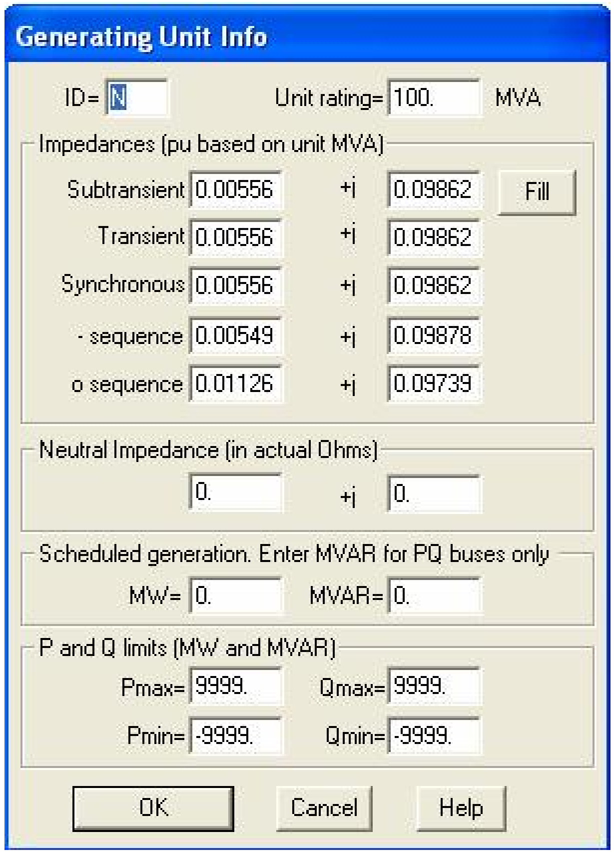

Fig B.10 Generator source impedance

VITA

Cesar Alberto Rincon was born May, 1982, in Guayaquil, Ecuador. His career started in 2005 when he graduated from The University of New Orleans with a bachelor’s in electrical engineering. He worked as the Systems and Network Administrator at the College of Engineering before graduation. During his senior year, he was an engineering intern with the Systems Engineering group at the Transmission Division of Entergy Corporation. After graduation, he worked as a contract engineer until he started graduate school in January 2007. He worked as a research assistant for the spring semester 2007 and then he went back as an engineering intern for the same group at Entergy for the reminder of the year. In January 2008, he accepted a full time position in the Settings and Configurations group of Entergy. He’ll hopefully be awarded the degree of Master of Science in Electrical Engineering in August 2008