1
INTRODUCTION

1.1 Bulk Power Transmission [1]

Power is the basic need for the economic development of any country. Availability of electricity has been the most powerful vehicle of introducing economic development and social change throughout the world. Governments across the globe have to give highest priority to the programs related to generation, transmission and distribution of electrical energy economically and efficiently in the planning commissions to be followed.

Engineers design transmission networks to transport the energy as efficiently as feasible, while at the same time taking into account economic factors, network safety and redundancy. These networks use components such as power lines, cables, circuit breakers, switches and transformers. A transmission substation decreases the voltage of electricity coming in allowing it to connect from long distance, high voltage transmission, to local, lower voltage, distribution. It also reroutes power to other transmission lines that serve local markets. The substation may also "re-boost" power allowing it to travel greater distances from the power generation source along the high voltage transmission lines.

Transmission efficiency is improved by increasing the voltage using a step-up transformer, which reduces the current in the conductors, while keeping the power transmitted nearly equal to the power input. The reduced current flowing through the conductor reduces the losses in the conductor and since, according to joules law, the losses are proportional to the square of the current, halving the current makes the transmission loss one quarter the original value. For reduction of the cost and improved reliability of electrical power the two most important factors are bulk power transmission and interconnections off power systems.

The power transfer capability equations for a transmission network can be written as:

$$P=V_1V_2 \sin \varnothing / X \quad (1.1)$$

(V_1 = Sending end voltage, V_2 = Receiving end voltage, $\varnothing$= Angular difference between voltages at the two ends of the line, X = Net Reactance of the line= $X_L - X_C$)

Based on the same the transmission system is suppose to deliver bulk power from power stations to the load centers to domestic, agricultural and industrial consumers. With all the modern technologies to transmit, control / regulate and convert the power from one form to another. Some inherent limitations of bulk power transmission is faced by modern power system engineers.

The origins of the limits vary depending on the length of the line. For a short line, the heating of conductors due to line losses sets a "thermal" limit. If too much current is drawn, conductors may sag too close to the ground, or conductors and equipment may be damaged by overheating. For intermediate-length lines of the order of 100 kms, the limit is set by the voltage drop in the line or voltage regulation standards of the utilities for the line. For longer AC lines, system stability (transient stability limits) sets the limit to the power that can be transferred.

Approximately, the power flowing over an AC line is proportional to the sine of the phase angle between the receiving and transmitting ends. Since this angle varies depending on system loading and generation, it is undesirable for the angle to approach 90 degrees. Very approximately, the allowable product of line length and maximum load is proportional to the square of the system voltage. Series capacitors or phase-shifting transformers are used on long lines to improve stability.

1.2 Series Compensation Technique & its Advantages [2]

For transmission of large amounts of electric power, AC transmission line in the overwhelming majority of cases is the established as well as the most cost effective option at hand. In cases of long distance transmission, as in interconnection of power systems, care has to be taken for safeguarding of synchronism as well as stable system voltages in the interconnection, particularly for extreme load conditions and in conjunction with system faults. With series compensation, the viable distances of AC power transmission become sufficiently large to remove altogether the issue of distance as a limiting factor for AC transmission in practice in most cases. Series compensated AC power corridors transmitting bulk power over distances of well over 1,000 kms are a reality today.

Series compensation has been in commercial use since the early 1960's. Series compensation reduces transmission reactance at power frequency, which brings a number of benefits for the user of the grid, all contributing to an increase of the power transmission capability of new as well as existing transmission lines. These benefits include:

· An improvement in system stability.

· Improvement of voltage regulation and reactive power balance.

· Improved load sharing between parallel lines.

· In many cases, a reduction in transmission losses.

The impact of series compensation on power transmission capability can be illustrated as in Fig.1.1. Here, the quantity k is the degree of compensation of the series capacitor, equal to the relationship between the capacitive reactance of the series capacitor (X_C) and the inductive reactance of the transmission line (X_L). ⌀ is the angular difference between end voltages of the line. For a fixed angular difference, the active power transmission capability of the line increases as the degree of compensation increases. Vice versa, for a fixed amount of power transmission over the line, the angular difference decreases as k increases, which is a measure of increased dynamic stability of the transmission system. Whether a series capacitor is installed to bring about an increase in power transmission capacity or increased dynamic stability at a fixed power transmission level, is purely a matter of application in each particular case.

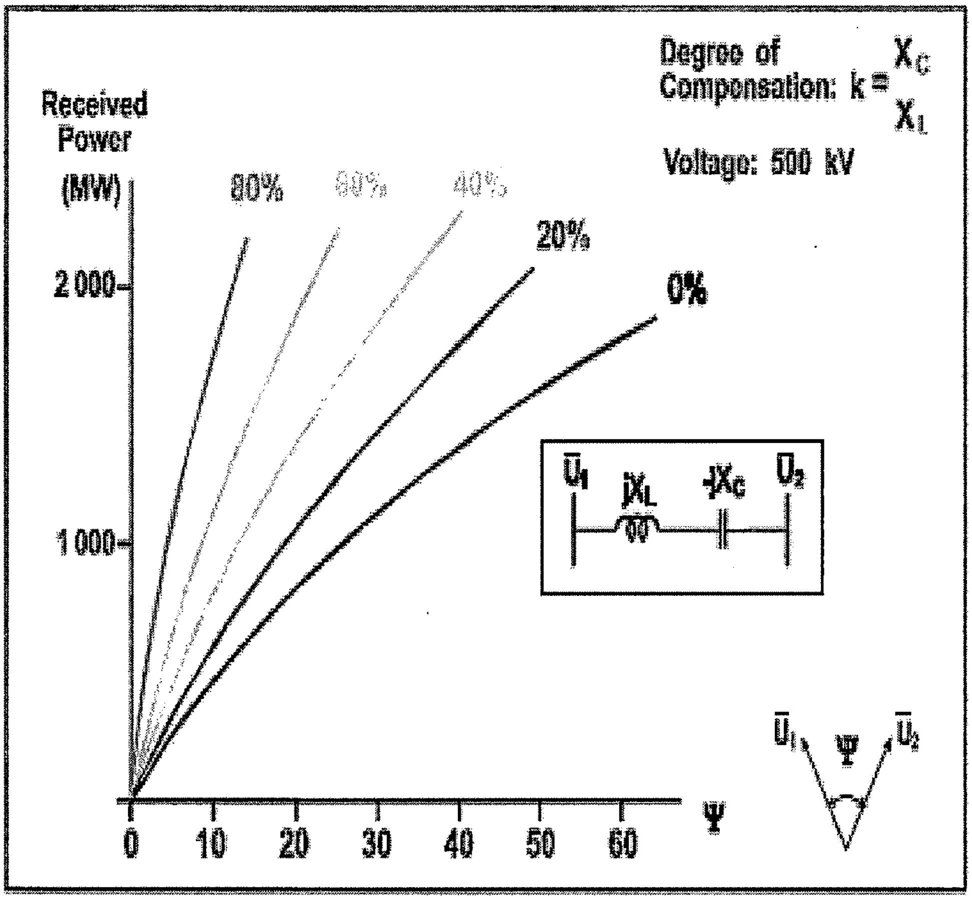

Fig.1.1-Impact of Series Compensation (where Ψ= ø = angular Displacement in Line End Voltages In degrees)

1.2.1 Series Capacitor Typical Set-up

A series capacitor is not just a capacitor bank in series with the line. For proper functioning, series compensation requires control, protection and supervision facilities to enable it to perform as an integrated part of any power system. Also, since the series capacitor is working at the same voltage level as the rest of the system, it needs to be fully insulated to ground.

The typical set-up circuit diagram of a state of the art series capacitor (in general) is shown in Fig.1.2. The main protective device is a varistor, usually of ZnO

The typical set-up circuit diagram of a state of the art series capacitor (in general) is shown in Fig.1.2. The main protective device is a varistor, usually of ZnO (Zink Oxide) type, limiting the voltage across the capacitor to safe values in conjunction with system faults giving rise to large short circuit currents flowing through the line. A spark gap is utilized in many cases as back-up protection, to enable the by-pass of the series capacitor in situations where the varistor is not sufficient to absorb the excess current during a fault sequence. Finally, a circuit breaker is incorporated in the scheme to enable the switching in and out of the series capacitor as need may be. It is also needed for extinguishing of the spark gap, or, in the absence of a spark gap, for by-passing of the varistor in conjunction with faults close to the series capacitor (so-called internal faults).

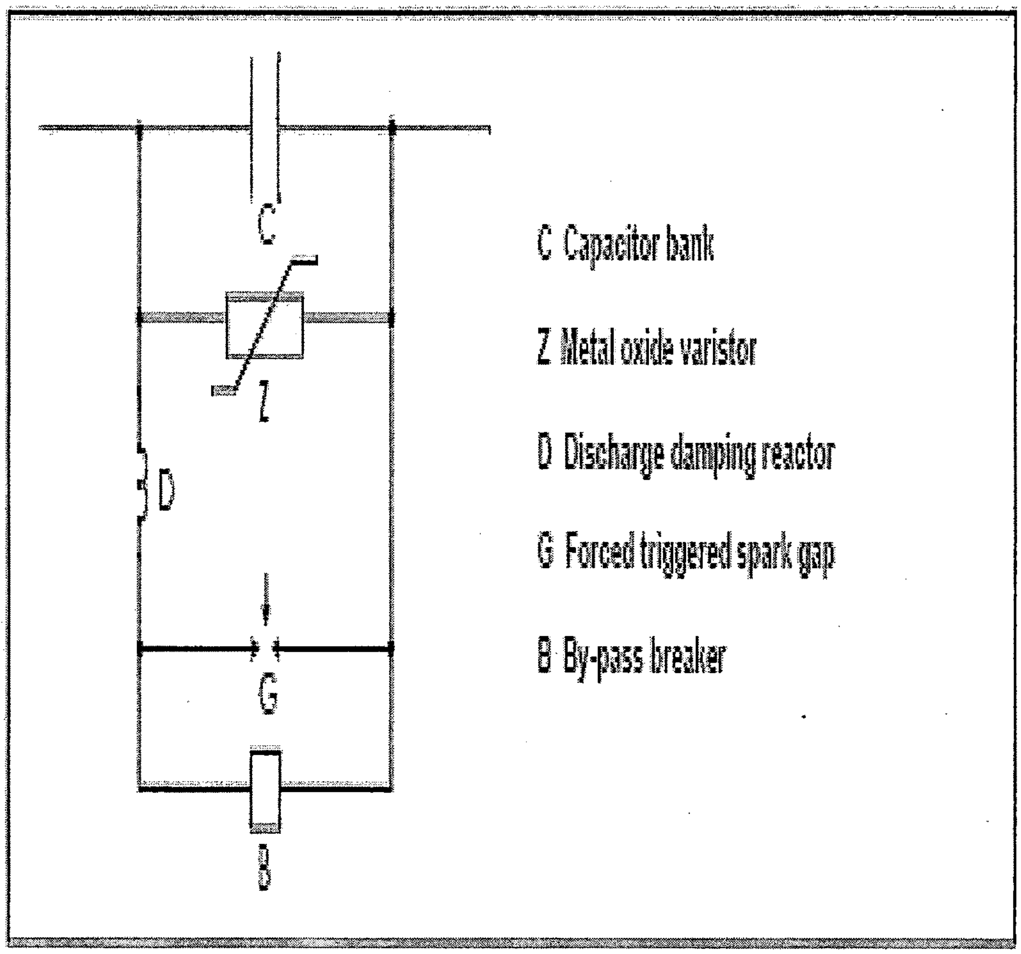

Fig.1.2-The typical Set-up circuit diagram of a Series Capacitor

1.3 Overview of Principles of Distance Protection for Transmission Lines [3]-[4]

In order to intelligently discuss the problems associated with distance protection for series compensated transmission lines, one must first have a firm understanding of the principles and problems associated with the protection schemes used on non-compensated transmission lines. Once these basic principles are understood, an attempt can be made to solve the additional relaying problems caused by the introduction of the series compensation capacitors.

1.3.1 Commonly Used Methods Available for Distance Protection of Transmission Lines

There are three major categories of protection schemes for transmission lines. Two are known as distance protection schemes. These are "Pilot Protection" and "Non-Pilot Protection". The term "pilot" referring to the use of a communications link between the ends of the line to be protected (allowing for instantaneous fault clearing). In pilot schemes, there is the advantage of "knowing" the conditions of the line at both ends. The third type of approach is differential in nature. Phase comparison relaying is one of these. This allows for one fairly common solution to the problem of series compensated transmission line protection which is successful in most cases. This solution does not use distance relaying principles, instead it compares the phase of the currents at both ends of the line to see if there is a fault in the middle. This will be discussed more fully later. Aside from phase comparison relaying, there are a number of other pilot type protection schemes to choose from, some of which make use of impedance measurements (distance relaying schemes) and some do not. All of those which take into account impedance measurements must also allow for multiple zones or "stepped" distance protection. The same applies to all distance protection schemes which are non-pilot based.

One of the most critical issues in power system protection of any kind is the speed with which a fault can be cleared. Due to uncertainty in impedance measurements, when protecting a transmission line with non-pilot distance protection schemes (and some types of pilot protection schemes), it is necessary to rely on "stepped" zones of protection. This technique protects any given section of transmission line with multiple zones. Close in faults are cleared instantaneously by zone 1 protection. This protects roughly 85-90% of the line. When a fault is at 95% of the line its location becomes uncertain, based again on accuracy of impedance measurements, whether the fault is actually on that particular section of line or on an adjacent section. Therefore, it makes sense to delay tripping of faults which are perceived by the relay to be between the zone 1 upper limit and the zone 2 upper limit (120-150%) of the length of the line in question. Zone three provides backup for neighboring lines. Delaying a trip on zone 2 and 3 faults allows time for a zone 1 reaction of the relay on the adjacent line if the fault is in fact on that section of line. If it is actually at 95% of the line in question, then it will be cleared in zone 2. This delay insures proper coordination, and helps in the effort to avoid shutting down longer sections of line than are necessary to clear the fault. See figure 1.3.

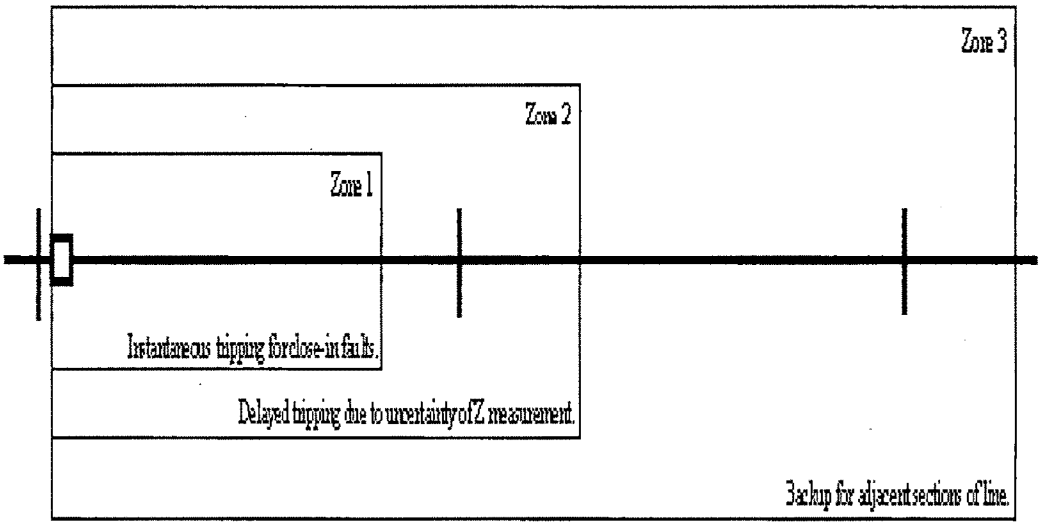

Fig.1.3 – Stepped Distance Relaying Zones

Clearly, the problem with all of this lies in faults which are in zone 2. These faults will NEVER be instantaneously cleared from remote ends. Therefore, these faults have the potential to be more damaging to the system as well as system stability immediately following the fault.

The biggest problem with pilot protection schemes unfortunately is the pilot (communications link). These communication channels are typically the weakest link in the system and most likely to contribute to the failure of the scheme. Further, they are quite expensive to install and require more maintenance when compared to non-pilot schemes. It is common practice to have a pilot and a non pilot protection scheme for most high voltage transmission lines. Therefore, later on in this document, the concentration will be mainly on the use of non-pilot protection methods for compensated lines.

1.3.2 Non-Pilot Distance Protection of Transmission Lines

As mentioned before, all non-pilot distance protection schemes are based on impedance measurement (or admittance, reactance etc). Therefore, the non-pilot schemes have some advantages and some disadvantages. The primary advantage to the use of non-pilot protection is that there is no need to construct the communications link (be it PLC, fiber optic, copper, microwave etc.). This is a tremendous cost savings to begin with as none of these methods are cheap. Copper wiring is only good for lines no longer than a couple of miles due to the expense of the high insulation copper cable and the induced current from neighboring power circuits.

In an attempt to better comprehend, visualize, and diagnose the operation of impedance based relays, the R-X diagram is used. This diagram (Fig.1.4) permits the use of only two quantities R and X (or Z and q in polar form) instead of the confusing combination of E, I, and q. Further, we are able to represent the relay characteristics as well as the system characteristics on the same diagram and quickly determine at a glance what conditions will lead to relay operation.

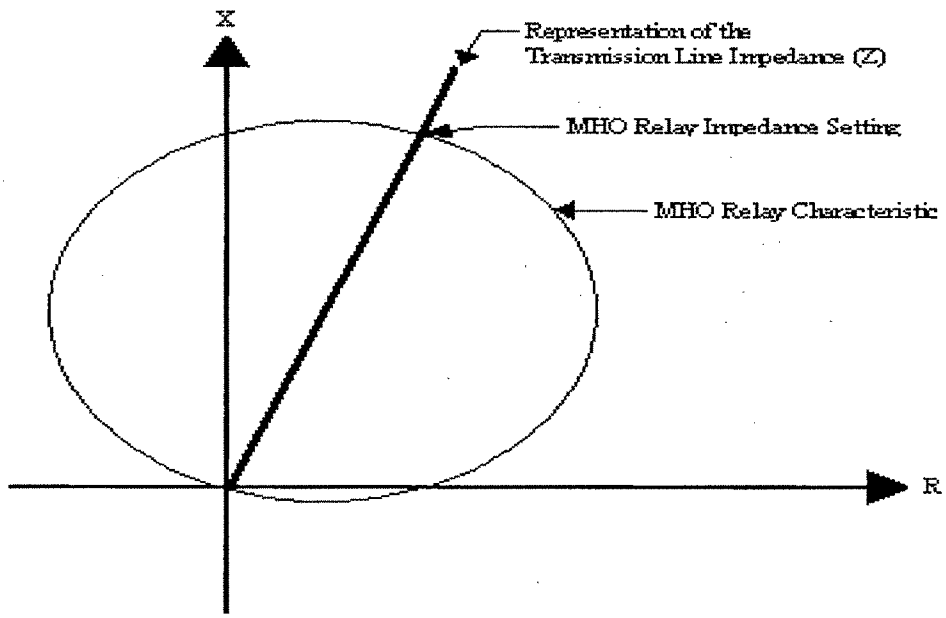

Fig.1.4 – Typical Impedance Diagram Showing Line and MHO Relay Characteristic

If we consider a three phase power system, there are a total of 10 different types of faults which are handled by 6 relays for each transmission line. These include 3 phase distance relays, and 3 ground distance relays. With all cases, it should be kept in mind that regardless of the type of fault in question, the voltage and current used to energize the relay are such that the relay will measure the positive sequence impedance from the relay location to the fault.

Once the positive sequence impedance of a fault is known, it should be quite easy to determine the location of the fault and thus make a relaying decision. The only problem which creeps into the computation is fault resistance. In the case of phase to ground faults this is a more serious problem as there is the fault arc resistance in series with tower, footing, and grounding resistances. However, all fault types are subject to the varying arc resistance phenomenon. Therefore, it is of importance to discuss the effect of this resistance on relaying computations and more specifically, the characteristic of the relay itself. As far as the tower footing resistance is concerned (in phase to ground faults), it is roughly a constant between 5 and 50 ohms. This can be compensated for by adding width to the relay trip characteristic on either side of the apparent impedance representing the line. This effectively covers all possible scenarios. As far as fault arc resistance, a generally accepted formula for estimation is:

$$R_{arc} = 76V^2 / \text{Short Circuit KVA} \quad (1.2)$$

In the above equation, V represents the system line to line voltage in kV at the fault location. A worst case can be computed for this value and added to the resistance reach in the relay trip characteristic.

This leads us to the consideration of transmission compensation devices and their effect on relaying. A series capacitor creates a discontinuity in the apparent impedance of the transmission line as viewed from the relay site. This is due to the negative reactance value of the capacitor. Therefore, close in faults appear to be reverse faults as the reactive component of the fault impedance seen is negative. This causes security problems as the relay will be likely to trip for faults which it should not. On the flip side of the coin, under certain conditions, faults near the far end of the line may appear to be outside of zone 1 and may not trip in zone 2 operating time. This problem causes lack of fast clearing for faults that should cause a trip.

The problems with protecting series capacitor compensated lines are complicated further by the protection schemes used for the capacitor itself. These schemes may incorporate spark gaps (introducing a varying resistance component), Metal Oxide Varistors (introducing a varying and nonlinear resistance), or a circuit breaker which closes during faults creating a bypass around the capacitor for high fault currents (thus introducing uncertainty into the calculation).

There are two main solutions in use today to combat the problem. In non-pilot and some types of pilot schemes, there is a time delay which gives the capacitor's protection time to act and effectively remove the capacitor from the circuit altogether. Then, the impedance calculation should be accurate. In pilot schemes such as phase comparison relaying, this is not necessary, however these pilot schemes have drawbacks which will be discussed later.

There is another important point to consider. As the load on a transmission line increases, the impedance seen by the relay decreases. At a certain point, the relay will confuse normal load for a fault. This point, known as the load-ability limit of the relay is an important constraint to be considered in the selection of a relay characteristic.
Some characteristics will allow for better load-ability than others.

1.3.3 Pilot Distance Protection of Transmission Lines

There are quite a few protection schemes which are based on communication links between the relays at the far ends of a given transmission line. This is in order to realize the benefits of having information from both ends of the line in order to make accurate relaying decisions. Most of these pilot schemes depend on a power line carrier (PLC). This popular method couples a tripping and/or blocking signal in the 10 to 490 kHz range onto the transmission line itself. Other methods for communication include microwave and fiber optic links. These have not been used as often in the past as power line carrier, however these methods are becoming more attractive as the technology becomes less and less expensive.

Pilot protection schemes can be divided into two categories, tripping and blocking. Blocking refers to the fact that the communications signal is used to "block" a trip. When a fault is detected and no blocking signal is present, a trip is issued. When the blocking signal is present, the other end of the transmission line is sending the signal "the fault is outside of our line" and the line does not trip. Conversely, a tripping scheme is one in which the presence of a communications signal indicates that a trip should be issued. Tripping is only used when an alternative communications link to the line itself is available. Blocking on the other hand is usually used only for PLC. The reason for this is simple. When a fault occurs on a transmission line which is making use of PLC, the signal between the two ends of the line can become severely attenuated. Under these conditions it is desirable to initiate a trip. Additionally, if a tripping scheme is used, the signal meant to initiate the trip could be lost and the line could fail to trip. Tripping is a viable option chosen when non PLC methods of communications are used such as microwave, fiber optic, or pilot wire. Further, it is better to use tripping methods when possible as they are faster since there is no need for coordination delays.

There are a number of problems that can crop up in a pilot protection scheme that must be considered. While there is the benefit of having information from both ends of the line, there is the potential for that communication to be lost due to the volatility of the communications link itself. When this happens, the scheme can fail in one of two ways. The relays involved can fail to operate (loss of dependability) for an actual fault as they do not see a "trip" signal from the opposite end of the line, or the relays involved can operate when there is no fault (loss of security) as there is no "block" signal seen.

Loss of communications is probably the biggest potential problem with a pilot scheme. Schemes such as directional comparison blocking will still trip for all faults for which they are supposed to, however they may also trip for faults for which they are not supposed to. Any fault picked up by the fault detector will cause a trip in the directional comparison blocking scheme if the communication link fails. This problem can be resolved by using a directional comparison unblocking scheme. This scheme is similar to directional comparison blocking, however in directional comparison unblocking there is a signal which is present all the time, (the blocking signal) not just when a fault is detected. This signal is a test to be sure that the communications link is operational. When an internal fault occurs, the carrier shifts frequency to an "unblocking" signal.

Then the relay is free to trip. This system is therefore capable of providing a warning immediately when there is a carrier problem instead of waiting for a false operation of the relay to indicate that there is a problem as would occur in the directional comparison blocking scheme.

Speed is always considered to be of paramount importance in protective relaying, particularly on EHV power lines where damage to equipment and deterioration of system stability occur very quickly when a fault is not cleared. The problem with using a blocking scheme is that there must be a coordination delay in order to allow time for the blocking signal from the opposite end of the line to start. Therefore it becomes desirable to implement a tripping scheme if a communications link other than the line itself is available.

Another serious problem which can crop up when using PLC is a false trip due to electrical noise which can be caused by switching in the substation, or transients due to other relay operations. These electrical phenomena can cause the PLC signals to be misinterpreted. To solve this problem, of course one would like to engineer in as much shielding and stabilization for the circuitry as possible and economical, however there are other tripping pilot schemes which help to make the system more secure. One such scheme is Permissive Overreaching Transfer Trip in which an overreaching fault detector is used. This scheme uses the directional overreaching relay as both a fault detector and a permissive interlock to prevent noise initiated trips.

There is another option in the family of pilot relaying schemes left to discuss. This method is Phase Comparison Relaying. This method does not make use of impedance relays as other methods do. Rather, the relative phase angle between the currents at the far ends of the line is compared. When these currents are in phase, it is obvious that the current is entering one end of the line and departing from the other and that there must not be a fault. When the currents are 180 degrees out of phase, there is clearly current entering the line from both sides and there is then clearly a fault on the line somewhere. Phase Comparison Relaying is of particular interest to this investigation as it will work properly for lines which are protected with series capacitors. It is the only scheme which will work accurately without modifications or the addition of time delays. Further, there is no need for PT's when using phase comparison relaying as the only concern is with the phase of the current. There is still however one drawback which is that this scheme is still a pilot scheme and therefore requires a communications link between the far ends of the line. The other down side is that this scheme does not provide back up protection for the line, or for the neighboring sections. In order to have some redundancy or a backup, another relay must be used.

1.4 The relaying Problems associated with Series Capacitor Compensation [3]-[6]

Protective distance relays, which make use of impedance measurements in order to determine the presence and location of faults, are "fooled" by installed series capacitance on the line when the presence or absence of the capacitor in the fault circuit is not known a priori. This is because the capacitance cancels or compensates some of the inductance of the line and therefore the relay may perceive a fault to be in its first zone when the fault is actually in the second or third zone of protection which is identified as Overreaching problem of distance relays. Similarly, first zone faults can be perceived to be reverse faults! Clearly this can cause some costly operating errors. Series Capacitors and their over-voltage protection devices (typically Metal Oxide Varistors, MOVs and/or air gaps), when installed on a transmission line, create, however, several problems for its protective relays and fault locators. Operating conditions for protective relays become unfavorable and include such phenomena as voltage and/or current inversion, sub-harmonic oscillations, and additional transients caused by the air gaps triggered by thermal protection of the MOVs.

Understanding the relaying problems associated with series compensated lines is much more difficult than uncompensated line relaying for a number of reasons:

(a) It requires a better feel for the transient response of transmission lines when faulted.

(b) It requires a better understanding of transient response of protective relays.

(c) The significant problems introduced by the series capacitors will vary considerably based on system configuration, line configuration, line length, % compensation, etc.

(d) The series capacitors tend to exacerbate problems associated with some uncompensated lines such as load flow problems, of un-transposed lines, mutual impedance problems, etc.

(e) The type of capacitor protection and the capacitor control can influence the significance of some problem areas.

As in all relaying, if the problem areas are anticipated and understood, the solution to the problem is achieved with comparative ease.

1.4.1 System Transients

Normally faults on to un-compensated lines will give rise to fault currents having mixture of steady state ac component current and decaying dc offset component. But in the case of series capacitor compensated line if the fault occurs towards the remote end of the line resulting in to capacitor as a part of the fault loop in post fault conditions will give rise to ac transient component along with steady state ac component. The frequency of such ac transient current component will be sub-harmonic and is given by:

fundamental * $(X_C/X_L)1/2$

where X_C is the total capacitive impedance in series with the total inductive impedance X_L If the "voltage drops" due to the load current are small compared to the "voltage drops" due to the fault current, then in the first half cycle of voltage after the fault incidence, the voltage drop in the inductor is essentially of the same polarity as the voltage drop in the capacitor as shown in Figure 1.5. Thus the capacitor tends to reduce the fault current initially, and then when the capacitor voltage shifts out of phase with the inductor voltage the current is larger than the current would be if the capacitor is bypassed. Due to this transient ac component the relay response to the positive and negative half cycle of the power frequency will be different and it may see the fault near to and away from it during the period of one power frequency cycle which makes it difficult for the relay to exactly identify the fault location.

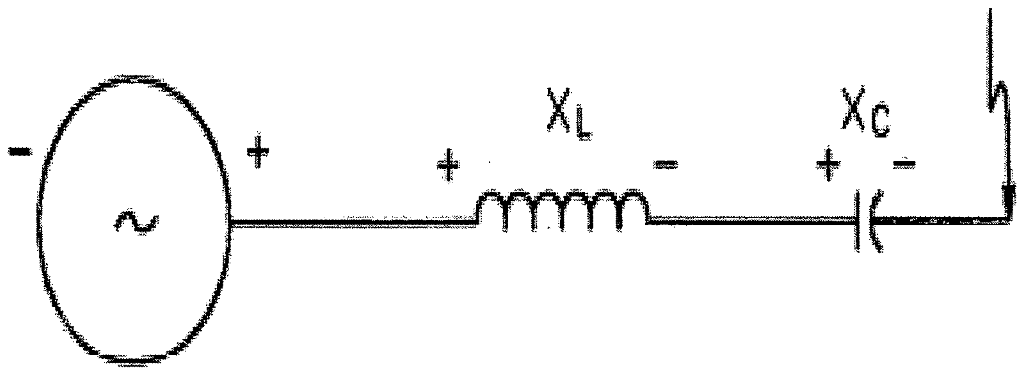

Fig.1.5-System Transient Condition

1.4.2 Capacitor Over voltage Protection

Early series capacitor designs utilized a trigger gap to bypass the capacitor bank (or section) when the voltage across the bank (or section) exceeded the trigger setting (called the protection level(s) in terms of steady state current that would cause triggering because low frequency transients in the fault current increases the instantaneous voltage across the capacitor well above the steady state voltage, the capacitors would be by-passed for fault currents (or switched load currents) well below the protective level.

The capacitors were bypassed through a current limiting reactor which produced a very large transient high frequency voltage across the capacitor bank. If the fault was close to the line side of the capacitor bank, the large high frequency voltage would appear on bus side potential devices and also the shunt capacitance in adjacent lines, requiring filtering on both the voltage and current circuits in the relays.

However, despite the need for filtering, the bypass gaps operating on lower current levels provided more security for relay systems on lines adjacent to the faulted line. Unfortunately, the reliability of the power system was jeopardized by bypassing capacitors on un-faulted lines by fault (or load) currents.

Now a days, instead of bypass gaps (or in addition to them) over voltage protection is accomplished by paralleling the capacitor bank by MOVs. When the peak voltage reaches the protective level, the MOV conducts, limiting excessive voltage across the capacitor. The MOVs would also conduct transiently on over voltages as a result of the low frequency current transients, thus providing attenuation for the low frequency transients. The amount of attenuation will depend on how much conduction occurs. If the MOVs conduct steady state then the parallel arrangement of the MOV and series capacitor will appear as a series combination of $X_{C'}$ and $R_{C'}$. The magnitude of $X_{C'}$ and $R_{C'}$can be calculated from the ratio of the fault current I_F to the protective level I_{PL} and the pre-fault capacitance of the bank. The values of $X_{C'}$ and $R_{C'}$ can then be used in steady state analysis of relay performance. For example:

when $I_F = 2.5\ I_{PL}$, $X_{C'} \approx 1/3\ X_C \approx R_{C'}$

when $I_F = 5\ I_{PL}$, $X_{C'} \approx 0.1\ X_C$, $RC' \approx 0.2\ X_C$.

The ratio of IF to IPL becomes the key indicator of potential problems with protection systems on series compensated systems.

1.4.3 Voltage Reversals

For the simple system shown in Figure 1.6, assume that the source impedance to the left of bus C is much larger than XC, so that the fault current through the capacitor is less than the protective level and lags the source voltage at the left by approximately 90°. The fault current at the two ends of the line CD will have an angular difference approximately equal to the load angle across the system .The steady state voltage at C will reverse with respect to the source voltage at the left.

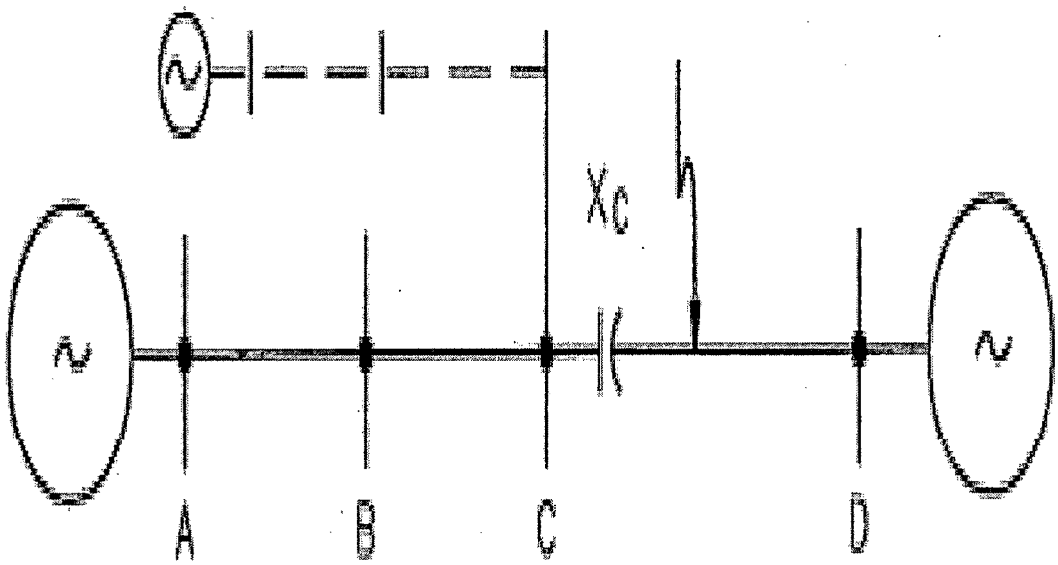

Fig.1.6-Voltage Reversal Condition

It is also possible that the voltage at bus B will also reverse if the voltage drop across the line BC is less than the voltage drop across the capacitor. This possibility will increase as the fault current over the dotted line increases. Hence one can conclude that for the system condition which leads the relays located at specific bus to experience voltage reversals, they will experience an increase of voltage in post fault condition then the pre fault condition on to series compensated lines while in general on the uncompensated lines the post fault voltages are always less then the pre-fault ones.

1.4.4 Current Reversals

In the system shown in Figure 1.7, the source impedance to the left of bus C is usually less than XC in normal power systems. Thus, if we ignore the capacitor over voltage protection, the fault current at the left end of the line would reverse because the net impedance between the fault and the left source would be capacitive. Thus the fault would appear as an external fault to either a phase comparison or a directional comparison relay system. However, in this theoretical case, the leading current through inductive source would cause the voltage across the capacitor to be substantially higher than rated voltage. Normal protective levels limit capacitive voltages below rated voltage, thus insuring a lagging component of fault current to produce a voltage drop in the source impedance.

The above discussion assumes a bolted fault without fault impedance. Ground faults may have sufficient fault impedance to limit the fault current magnitude below the protective level. Phase comparison relays would see the fault as external. A well designed directional comparison relay system would see the fault as an internal fault. If the inductive positive and negative sequence source impedances are greater than the capacitive impedance but the zero sequence source impedance was less than the capacitive impedance, there would be a fault current reversal between the zero sequence current at the right terminal and the positive and negative sequence currents at the right terminal.

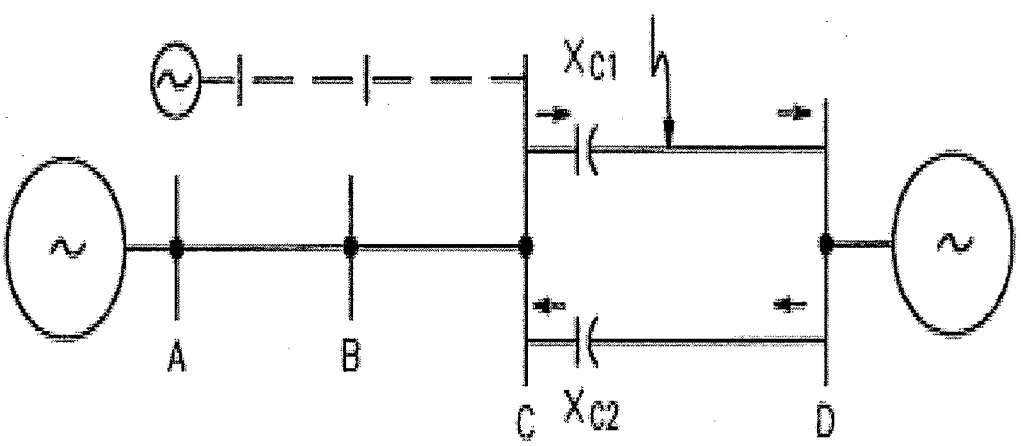

Fig.1.7 Current Reversal Condition

If the fault current through X_{C1} is greater than the protective level, then the MOV will conduct and X_{C1} in series with RC' with the magnitudes roughly and inverse function of the fault current. Thus, the remote end fault current can vary in phase angle with respect to the near end fault current from approximately zero to 180°. The actual configuration in your utility has a station tapped into one of the two parallel lines that will produce some degree of modification to the analysis stated above.

1.4.5 Overreaching of Distance relay due to Series Compensation

Overreaching of distance elements due to series compensation is probably the most critical and known consequence of Series Capacitor Compensation. The opposite may happen as well: a distance function may fail to pick up a low-current fault on the protected line. The problem of overreach of distance relays can be understood in detail by understanding the behavior of equivalent impedance offered by the combined equivalent circuit of series capacitor and MOV during the transient conditions of the power system.

1.4.5.1 Series capacitors and MOV's Equivalent Impedance

Vast majority of microprocessor-based distance relays respond to more (security) or less (speed) accurately filtered fundamental frequency components. Therefore, it becomes important to understand relations between the fundamental frequency voltage and current of a typical arrangement of Series Capacitors and their over-voltage protection devices.

Three single-phase banks of capacitors are used for series compensation. Each capacitor must be protected against over-voltages by air gaps or Metal Oxide Varistors (MOVs) or both. Under load conditions or low-current faults, the voltage drop across the SCs is below the voltage protection level: neither the air gaps nor the MOVs conduct any current. Therefore, the SC bank is equivalent to a pure reactance equal the reactance of the actual (physical) capacitor. Under very high current faults the voltage drop would be far above the protection level: the gaps and/or MOVs conduct majority of the through current, practically by-passing the Series Capacitors. Therefore, for large through currents the Series Capacitor bank is equivalent to a small resistance.

Between the two extremes there are situations when a comparable amount of current flows through the Series Capacitors and the MOVs. Fig.1.8 illustrates such a case. As the through current becomes larger, the voltage drop across the bank (Fig.1.8a) assumes more rectangular shape, being limited to the voltage protection level. The capacitors conduct the current during initial half-cycles (Fig.1.8b), while the MOVs conduct during the remaining halves (Fig.1.8c). The through current being a sum of the two is not distorted as compared with its two contributors, and is shifted in a leading direction with respect to the voltage drop across the bank. Relation between the fundamental frequency components of the voltage drop across the bank and the through current is resistive-capacitive impedance known as a Goldsworthy's equivalent.

Now Consider a parallel arrangement of an ideal capacitor (SC) and a non-linear resistor (MOV) shown in Fig.1.9a. Approximation of the MOV characteristic – accurate enough for protective relaying analysis is given by the following equation:

$$i = P \cdot \left(\frac{v}{V_{REF}} \right)^{q} \qquad \text{(1.3)}$$

where P and VREF are coordinates of the knee-point and q is an exponent of the characteristic (Fig.1.9c shows a sample MOV characteristic).

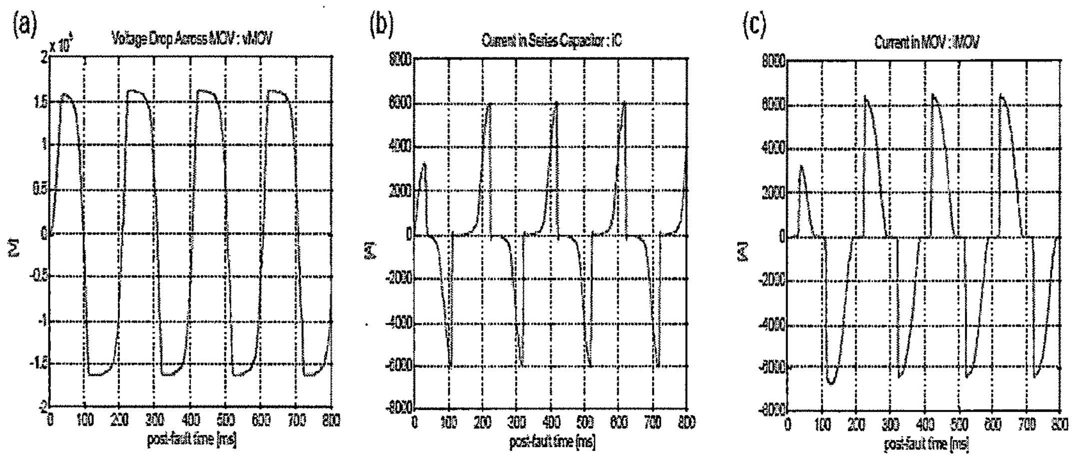

Fig.1.8-Series Capacitor with a conducting MOV (a) Voltage drop across MOV(vMOV in Volts)(b)Current in Series Capacitor(iC in Amps) (c) Current in MOV(iMOV in Amps)

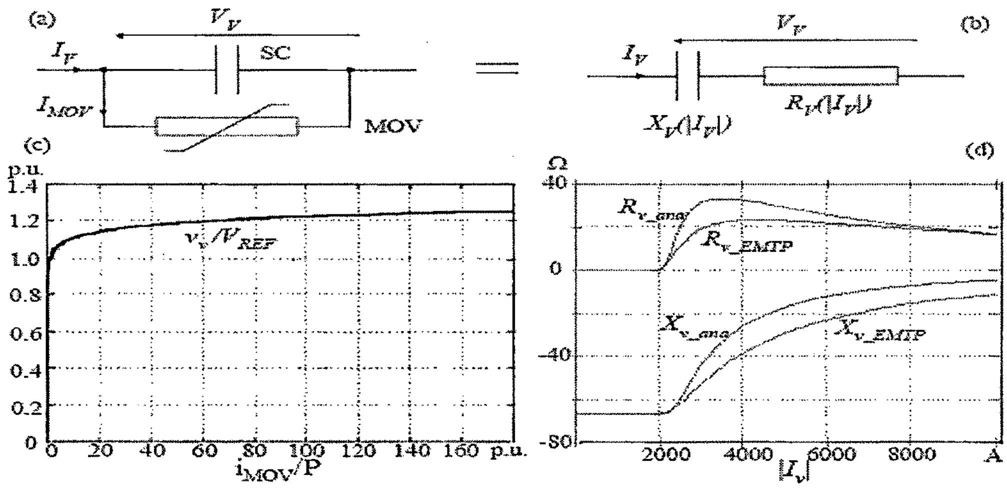

Fig.1.9-(a) Series Capacitor with MOV (b) Equivalent fundamental frequency impedance

(c) Sample MOV characteristic

(d) Sample current dependent parameters of equivalent impedance

For any operating condition of the parallel connection of Fig.1.9a one may calculate analytically, simulate using a transient program, or measure the fundamental components of the voltage across the bank and the through current. The ratio of such voltage and current Phasor is equivalent impedance (Fig.1.9b). It is obvious that the equivalent resistance and reactance are dependent on the through current (Fig.1.9d). For currents producing the voltage drop below the voltage protection level (2.4kA in this case study), the resistance is zero and the reactance equals the actual reactance of the SC (65 ohms in this example). For higher currents (3-4kA in this example) the resistance increases while the reactance consistently decreases. For very high currents, the reactance approaches zero so does the resistance. Fig.1.9d presents the equivalent resistance and reactance derived using two methods:

First, the EMTP simulations in a sample system have been performed [6] and the voltage and current waveforms with their natural distortions have been recorded. Second, the Fourier Transform has been used to calculate the Phasor and derive the impedance. The procedure has been repeated for various levels of the through current, resulting in a characteristic.

Second, a sinusoidal voltage drop has been assumed, while the through current, and subsequently the impedance has been calculated analytically.

The differences visible in Fig.1.9d result from various assumptions to calculating the Goldsworthy's model. Generally, the EMTP-type equivalent is more adequate for protective relaying studies, particularly if the Phasor were derived using the actual filtering techniques used by a protective relay under consideration.

The concept of equivalent impedance allows grasping the basics of the distance overreaching phenomenon. If the Series Capacitors are located between the fault and the relay potential point, the fault loop contains the line-to-fault impedance, fault resistance (if any) and the equivalent Series Capacitor & MOV impedance. The later being resistive-capacitive shifts the apparent impedance.

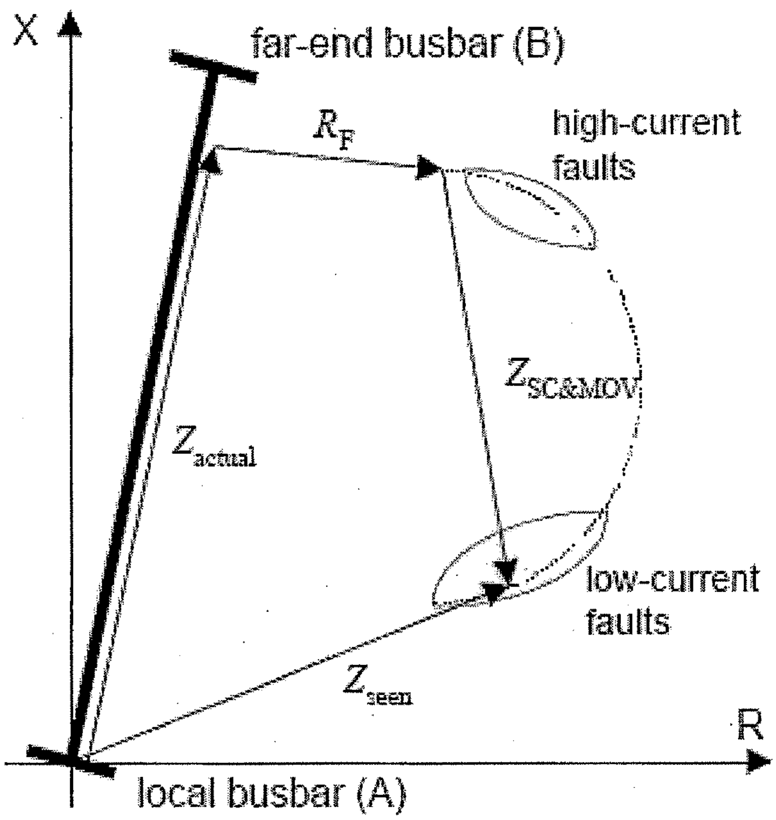

Fig.1.10-Distance Relay overreaching due to Series Compensation

Overreach is the primary consequence of the situation depicted in Figure 1.10. In the worst case – for low-current faults – the equivalent Series Capacitor & MOV impedance is a pure reactance shifting the apparent impedance down by the entire reactance of the physical capacitors. As the lines are typically compensated at the 50-70% rate, the overreach may be as high as 50-70%. For high-current faults, though, the equivalent Series Capacitor & MOV impedance shifts the apparent impedance only slightly to the right. There is no danger of overreaching in such case.

During medium-current faults on the line, the apparent impedance may be shifted to the right by more than half the reactance of the capacitors. This relocation may be high enough to push the apparent impedance outside the operating characteristic, particularly if a lens, conservatively set blinders, or load encroachment characteristics are used.

Another observation that can be derived from this simplified model is a failure of a distance function to respond to a low-current close-in fault. Under such a fault, the apparent impedance moves to the fourth quadrant of the impedance plane resulting in problems with directional discrimination.

The Series Capacitor & MOV bank acts as a "fault current stabilizer": for larger currents the capacitive reactance is smaller while the resistance is larger – this reduces the current as compared with a fully compensated circuit; for smaller currents the capacitive reactance is larger – this reduces the net impedance and increases the current as compared with a non-compensated circuit. As a result, the fault current versus fault location characteristic is flatter for series-compensated lines comparing with non-compensated lines.

Finally one can summarize the discussion with a conclusion that the overreaching of distance elements due to series compensation is probably the most critical and known consequence of Series Capacitor Compensation.

1.5 Work Objectives

The main objectives of the intended studies in this work are;

1. Recognizing and Understanding the problem areas associated with protection of Series Compensated Transmission Lines.

2. To work upon, develop and present some techniques using signal processing / analytical tools like Fourier and Wavelet Transform to prevent overreach/ mal-operation of distance relays for protection of Series Compensated Transmission Lines.

3. Testing the robustness of suggested techniques by extensive simulation studies.

1.6 Organization of the Thesis

The thesis progressively discusses the approach employed in order to meet the above objectives as follows;

Chapter 1 discusses importance of bulk power transmission and its limitations, Series compensation technique and its advantages, Series capacitor basic set-up, Fundamentals aspects of distance protection for the Transmission Lines and most importantly the relaying problems associated with series compensated transmission lines.

Chapter 2 discusses the fundamentals of Fourier transforms, its variants (DFT,FFT) and takes a in depth view of Wavelet Transform including its application to power systems.

Chapter 3 discusses the proposed "Percentage Harmonic detection based Non-Unit (Single Ended) Protection Technique using Fast Fourier Transform" to prevent overreach / mal-operation of distance relays for protection of Series Compensated Transmission Lines and results of related simulation studies.

Chapter 4 discusses the proposed "Current Differential Pilot Relaying (CDPR) Protection Technique using Wavelet Transform" for protection of Series Compensated Transmission Lines and results of related simulation studies.

Chapter 5 discusses the proposed "Fault Generated High Frequency Transients based Non-Unit (Single Ended) Protection Technique using Wavelet Transform" to prevent overreach / mal-operation of distance relays for protection of Series Compensated Transmission Lines and results of related simulation studies.

Chapter 6 discusses the conclusions from suggested techniques and related simulation studies done in the thesis. Possible steps for future developments and research in the area is also briefly suggested.