ABSTRACT

Power is the basic need for the economic development of any country. Availability of electricity has been the most powerful vehicle for introducing economic development and social change throughout the world. Engineers design transmission networks to transport the energy as efficiently as feasible 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 means that are universally adopted by engineers are bulk power transmission and interconnections of power systems. It requires Extra High Voltage (EHV) and Ultra High Voltage (UHV) transmission lines to be erected.

With all the modern technologies to transmit, control / regulate and convert the power from one form to another form some inherent limitations of bulk power transmission is faced by power system engineers. The origins of these 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. For intermediate-length lines of the order of 100 km, the limit is set by the voltage drop in the line or voltage regulation

standards of the utilities for the line. For longer (EHV and UHV) AC lines, system stability (transient stability limits) sets the limit to the power that can be transferred. Series Capacitor Compensation Technique is a well known method to increase power transfer capabilities of the long lines while improving stability of the system. 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 km are a reality today.

Series compensation has been in commercial use since the early 1960s. Series compensation reduces transmission reactance at power frequency, which brings a number of benefits for the user of the grid (Improved system stability, Improved voltage regulation and reactive power balance, Improved load sharing between parallel line, reduction in transmission losses) all contributing to an increase of the power transmission capability of new as well as existing transmission lines.

Unfortunately, the series capacitor can undermine the effectiveness of many of the protection schemes used for long distance transmission lines. The introduction of the capacitance in series with the line reactance adds certain complexities to the effective application of impedance based distance relays. The relay will attempt to look at the ratio of voltage to current to determine the distance to the fault in order to decide if the fault is in or out of its zone of protection. It is certainly possible to correct the settings of the relay when it is known that the capacitor is always going to be a part of the fault circuit. However, that is not always known. By canceling some of the line's series inductance, the series capacitor can make remote forward faults look as if they are in zone one of the relay when the capacitor is switched into the transmission line circuit and the relay setting rules are based on no capacitor in the fault loop and subsequently causing the relay to "overreach". 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 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 Metal Oxide Varistor. The Series Capacitor & Metal Oxide Varistor bank (equivalent circuit during a fault) acts as a "fault current stabilizer"; i.e. for larger fault 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 it can summarized that the overreaching of distance elements due to series compensation is probably the most critical and known consequence of Series Capacitor Compensation.

Numbers of solutions have been proposed for the protection of series compensated transmission lines. However, there is always a scope of improvement. Keeping in view of the above points, an attempt has been made in this thesis to work upon, develop and present some techniques using signal processing / analytical tools like Fourier and Wavelet Transforms to prevent overreach and mal-operation of traditional distance relays for protection of Series Compensated Transmission Lines. The work presented in this thesis addresses the problems encountered by conventional non-pilot distance relay when protecting series compensated transmission lines. The detailed analysis of the apparent impedance as seen from the relaying point is studied and elaborated taking into account the various effects associated with series compensated transmission lines. The work proposes three techniques towards the possible solution of problems encountered in protection of series compensated transmission lines.

Metal Oxide Varistors are typically placed in parallel with series capacitors. They are crucial in the protection schemes of these capacitors. When a fault occurs and line current surges to a level significantly higher than normal, damage to the dielectric in the capacitor can occur. The Metal Oxide Varistors, placed in parallel with the capacitor, prevents this by acting in a manner similar to a Zener diode; i.e. when the voltage is below the protection level of Metal Oxide Varistor, the device has very high resistance. However when the voltage exceeds the level set for the device, its resistance drops very quickly and acts to short the terminals of the capacitor in order to protect the dielectric from the damaging effects of a flashover. The device however can cause problems due to its highly non-linear nature. The resistance of this device will vary as the voltage on the capacitor terminals varies. There is however a positive side effect to all of this. When the Metal Oxide Varistor does operate (keeping in mind that not all faults will induce a current level sufficient to pass the MOV voltage threshold and activate the device), it creates a frequency signature which can be positively identified. When there is operation of a Metal Oxide Varistor, it is obvious that a series capacitor was part of the fault loop since only fault current would cause a Metal Oxide Varistor to operate and clip the voltage waveforms seen by the relay. A current controlled harmonic index based unit (Single ended) protection technique using Fast Fourier Transform (FFT) is proposed in this thesis in order to identify the presence of the capacitor in the fault loop in post fault scenario by identifying specific frequency signatures in voltage signals at relaying bus.

Nowadays the trend is to locate faults quickly, reliably and, if possible, without human intervention. This is made directly possible by utilizing fault generated signals. A fault produces a wide spectrum of signals that contains information about the fault distance. These signals are the power frequency component and the transients. The transients can be used in fault detection, classification and location for protection purpose instead of the power frequency. This is possible because the fault transients develop much faster and are less dependent on network configuration than the power frequency component. Hence, the fault generated high frequency transients can be used for detection, classification and location of the faults on any kind of transmission network. A unit (double-ended), Current Differential Pilot Relaying (CDPR) protection technique is proposed in this work for detection, discrimination, classification of faults for series compensated transmission. Wavelet transform is used as a signal processing tool where Instead of directly comparing the currents captured from Current Transformers, "the fault generated high frequency transients typical signature or fault spikes, as it appears after processing post fault signals at relaying terminals at the ends of the transmission line" is used as a control variable so that the influence of line charging capacitance will be reduced.

A perfect transmission line protection scheme is expected to differentiate the internal faults from external using one end measurements only. The conventional distance relaying which detects and classifies the faults (based on fundamental frequency components of the fault signals), mal-operates when applied for protection of series-compensated transmission line equipped with MOV especially when the faults are near towards the end of the protected zone. The bus-bar of the power system is always connected to many power system equipments. In case of bus-bar, its impedance to earth is mainly determined by these equipments' capacitance and capacitive coupling to earth. Hence when dealing with fault-generated high-frequency signals which travel along the line, the bus-bar stray capacitance (between bus-bar and earth) offers these signals low impedance path due to which a large amount of generated high frequency signals (ranging from 50 KHz-100 KHz) are directed to earth. On the other hand, the lower frequency signals (in the range of 500 Hz-3 KHz) are not affected by bus-bar stray capacitance. This criterion can be used as the key for development of fault generated high-frequency signal based protection scheme for deciding the two boundaries of the protected zone by the relay. Based on the above key factors a non-unit (Single-ended) protection scheme {for detection of fault, discrimination between fault zone (Internal or external Fault) and classification of the fault type} for series compensated transmission line is proposed in this thesis.

Wavelet transform is effectively utilized for extracting spectral energy associated with two distinct frequency bands (detail coefficients), which is utilized further for fault detection, fault zone discrimination and fault type classification.

In order to evaluate the performance of the proposed techniques in this work, extensive fault simulation studies are carried out on a series compensated transmission line model (mid-point compensated line). The fault data sets are generated using the well-known MATLAB (SIMPOWERSYSTEMS BLOCKSET) program. Fast Fourier Transform (FFT) GUI (Graphical User Interface) and Wavelet toolbox available in MATLAB is also utilized. The performance of the proposed techniques is analyzed for a large test data set considering a wide variation in system condition along with a change in the source impedance. The promising results of simulation studies indicate that the proposed techniques are fast, highly accurate, reliable and robust.

The summarized flow of the reported work chapter wise is given below;

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 Transforms including its application to power systems.

Chapter 3 discusses the proposed "Percentage Harmonic detection based Non-Unit (Single Ended) Protection Technique using Fast Fouñier Transforms" to prevent overreach and mal-operation of traditional and digital 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 Transforms" 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 Transforms" to prevent overreach and mal-operation of traditional and digital 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 results presented in the thesis. Possible steps for future developments and research in the area is also briefly suggested.

In summary, this thesis focuses on the problems encountered by conventional distance relay while dealing with protection of series compensated transmission lines, specifically focusing on problem of traditional distance relay overreach, and proposes three techniques towards detection, discrimination and classification of faults for series compensated transmission lines. A current controlled harmonic index based unit protection technique using Fast Fourier Transform (FFT) is proposed. A Current Differential Pilot Relaying (CDPR) based unit protection technique using Wavelet Transform is proposed. A fault-generated high-frequency transient based non-unit protection technique using Wavelet Transform is proposed in the thesis.