Chapter: I

Introduction

CHAPTER: 1
INTRODUCTION

1.1 General :

Due to the ever increasing demand of power supply, electric utilities all over the world are facing the pressing need to increase their transmission capacities in the next few years. The transmission of bulk power is also receiving greater importance because of the long distances between remotely located generating stations and load centres and the necessity to realize maximum benefit of reserve capability and diversity. The most common solution of increasing transmission capacity by increasing transmission voltages of A.C. overhead lines is likely to reach UHV levels in several parts of the world [1-5]. However, transmission of bulk power at EHV and UHV level has drawbacks such as introducing strong electric field at ground surface with possibility of adverse biological effects, audible noise, visual pollution and increasingly difficult problem of acquiring new Rights of Way (ROW) which is becoming more and more difficult because of public opposition and awareness of the adverse effects, growing importance of forest and high cost of land.

The EHV /UHV lines employ huge structures and the tower spoiling aesthetic beauty of land, leading to visual pollution. Even at HV and EHV levels, the problem of congested right of way exists especially in urban areas. The electric utilities are concerned to economize the use of land and to increase acceptability of overhead lines through reduced visibility and improved appearance. While these problems are being tackled at present through innovative design methods (including compaction, aesthetic design etc.) aimed at substantial reduction of sizes of multi circuit lines, the research and improvement of all viable alternatives are still in progress. Out of various transmission alternatives [1-8], multi-phase transmission (employing phase order more than three) is a unique approach for increasing transmission capability of over-head lines and it may be applied over the entire range of transmission voltages. Since the inception of concept in 1972, the multi-phase transmission research has made significant advances starting from investigation of basic feasibility to the construction and testing of experimental Six-Phase and Twelve-Phase lines and sub-stations.

A multi-phase transmission line offers several advantages over the conventional Three-Phase system viz. increased power transfer capability with efficient utilization of rights of way; reduced electrical environmental impact; compact structures; reduced unbalanced power due to possibility of symmetrical conductor arrangement; compatibility with existing systems and reduced overall cost etc. are some of the major advantages that accrue from the use of High phase order in transmission of power. Because of the aforesaid advantages, multi-phase systems (especially Six-Phase and Twelve-Phase) are being considered to be the potential alternative to the conventional Three-Phase system for the bulk power transmission.

The conversion of Three-Phase supply to Six-Phase with commonly available Three-Phase transformer connections, makes a Six-Phase system especially suitable for circuit uprating of certain existing double circuit Three-Phase lines. Some recent studies with regard to the development of this new power transmission technology contain very significant information regarding its basic feasibility; electrical and mechanical characteristics; economic viability; circuit uprating; mathematical modeling; design and analysis; construction of experimental line with associated hardware; substation and testing etc... which are, of course, preliminary in nature. However, a much more effort is needed to model, analyse and evaluate the performance of such a system both in qualitative and quantitative terms before it is realized in practice.

The present work is an attempt in this direction to derive line parameters, suitable mathematical models and equivalent circuits of multi-phase transmission line. These are at later stage used to carry out steady state analysis particularly the line Loadability study. Further analytical tools developed in the present work are employed to study the performance of multiphase system in comparison with the Gujarat Energy Transmission Company's (GETCO'S) Three-Phase Double Circuit System (TPDCS).

Before delineating the work reported in the thesis, a brief account of investigations of various aspects of multiphase system is presented in the following section.

1.2 Literature Review

The concept of multi-phase transmission emerged for the first time in 1972 at CIGRE meeting where Barthold et al. [8] presented calculation of power density of open wire transmission system. It was shown that ultimate power density capability is about 12000 MW/m^2 which is several times more than what is achieved by usual Three-Phase line. Thus the idea of higher space utilization of right of way corridor came into being with the use of high number of phases (more than three) as one of the options permitting increased power transfer without any increase in space requirements. The multi-phase line can either be used as a completely new line or it can be extended to up rate the existing Three-Phase double circuit line with or without reconductoring.

Multi-phase system, at present, is an interesting field of research in power system and following section attempts to present the work that has been carried out on the different facets of this new technology with the under-mentioned headings.

Basic feasibility:

The basic feasibility of multiphase transmission, especially, the Six-Phase transmission has been studied by Venkata et al. [9]. Several aspects like power transfer capability, load flow, stability and reliability were examined in the preliminary manner. Guyker et al. [10] have carried out investigation on the feasibility of 138 KV Six-Phase transmission by converting Three-Phase double circuit line to six-phase. The investigation highlighted several performance characteristics of 138 KV Six-Phase system, Three-Phase/Six-Phase transformation scheme, line tapping problem, over voltages, protection scheme, operational consideration etc. Stewart et al. [11,12] have systematically investigated multi-phase systems from steady state considerations as well as from considerations of over voltages and insulation requirements. The study [11] specifically addressed definition of the system voltage nomenclature, steady state operation as affected by line impedance, line and generator imbalances, and electrical environmental aspect of radio noise, audible noise and electric field at the ground surface. The study of over voltage and insulation requirements involved determination of over voltages due to inter-phase coupling, switching surges, rate of rise of recovery voltage and lightning surges. The effects of wind, ice, fault currents and phase spacer performance on conductor spacing were examined. Quantitative results for these areas were compared with Three-Phase system in both the studies [11, 12]. Subhas et al. [13] reported on the feasibility of the 462 KV Six-Phase transmission as an alternative to the 800 KV Three-Phase Double Circuit transmission system. Weedy [14], Begamudre [15] and Singh [16] have described certain features and feasibility of multi-phase system based on the study reported in literature.

Component Transformation:-

For the purpose of unbalanced analysis and particularly fault analysis, a number of investigations have been directed to derive various component transformations for the multi-phase systems. The symmetrical component transformations for the Six-Phase system were derived by Bhatt et al [17] as a straight forward extension of Three-Phase technique; whereas Stewart et al [11] derived these transformations for Twelve-Phase in the same manner. Singh et al [18] derived power invariant, symmetrical components and Clerke's component transformation system for the Six-Phase system based upon symmetry consideration. These transformations were further extended for generalized ground n-port networks [19].

Willems [20-22] developed these transformations for the Six-Phase system by considering Six-Phase as two coupled Three-Phase systems. The method can be extended for the phase order in multiple of three. Peeran et al [23] derived a generalization of alpha-beta-zero component transformation for diagonalisation of the Six-Phase transmission system impedance matrix. Chandrasekaran et al [24] proposed a new transformation which leads to two sets of the familiar Three-Phase symmetrical components. However, it is to be noted that the impedance matrices of the lines (only cyclically transposed) cannot be diagonalised by Clerke's component transformation system or its variants, but only by symmetrical components transformation.

Transformation for Multi-phase Conversion:-

If a multi-phase transmission becomes a reality, Three-Phase / multi-phase transformers will be required at all levels in power system networks. A Six-Phase conversion can easily be achieved through certain connection schemes employing Three-Phase units. Such connection schemes are reported in several text books and reports [10, 16, 25, 27] while twelve- phase conversion schemes through synchronous converters and valves are reported in [26-30].

Willems [25] developed mathematical description of various Three-Phase / Six-Phase transformers. These transformers are considered as ideal, ignoring the leakage impedances of their windings. The phase coordinates as well as symmetrical components transformation were obtained [25]. A more realistic representation of wye / star, Three-Phase to Six-Phase transformer taking the leakage impedance and admittance into consideration, was derived by Tiwari et al [31]. In the study, a lattice equivalent circuit, nodal admittance matrix and the connection table for such transformers were developed. The transformer models were further improved by considering the off-nominal tappings on one of the windings by Tiwari et al [32], and general nodal representations of transformer applicable for different types of connection schemes were obtained. Tiwari et al [32, 33]. Three-Phase / Six-Phase transformer models, suitable for unbalanced network analysis, including off-nominal tappings were presented. Saleh et al [36] deployed mathematical representations for various Three-Phase / Six-Phase transformer in phase coordinates. Further, Chaudhary et al [37] extended these mathematical representations for wye / n-phase star transformer with considerations of leakage impedance /admittance and off-nominal turns ratio on primary side.

Transmission Line Models:-

Multi-phase transmission lines were modeled by phase impedance matrix by Bhatt et al [17], Willems [20] and Singh et al [18]. The problem of transposition of conductors was discussed by Stewart et al [11] and Willems [20]. Willems [25] also modeled Six-Phase line by ABCD-parameters. Employing Three-Phase / Six-Phase transformer descriptions, Six-Phase line integrated with the three-phase network was discussed by several authors [18, 24, 25, and 28] to obtain Three-Phase equivalent representation of Six-Phase line. The Six-Phase equivalent of Three-Phase line for carrying out analysis on Six-Phase side has also been discussed [25,37]. Some of these approaches have been generalized to n-phase order system by Chaudhary et al [37]. Swarup et al [38] made an attempt to model Twelve-Phase transmission line by employing wye /star Three-Phase / Twelve-Phase transformer in various ways.

Mixed Three-Phase and Six-Phase Network Analysis:-

Development of analytical tools for a mixed Three-Phase and High Phase order network has been an essential feature of multi-phase system analysis. It is believed that multi-phase transmission whenever realized, will be connected to a Three-Phase network invariably through these interfacing transformers. The analytical methods have relied on representing the multi-phase network by equivalent three-phase network [25, 31, 32, 33, 37, 38], containing in terms of transformed components on either side [40]. More recently a description of a mixed Three-Phase and Six-Phase systems in terms of sequence components at the Three-Phase network as well as in terms of Six-Phase sequences at Six-Phase network, was discussed by Auguglario et al. [4l].

Equivalent schemes at the Three-Phase sequences of Three-Phase to Six-Phase transformer were given. Willems [42] presented a new approach to the analysis of mixed Three-Phase and Six-Phase power systems, wherein it has been shown that the analysis of composite system can be reduced to the analysis of a Three-Phase power system by means of newly defined components. Different types of Three-Phase to Six-Phase power transformer representations were given. While the methods of fault analysis of a mixed Three-Phase and multi-phase systems were developed by Gross et al. [49] and Onogi et al. [45]; the load flow analysis and transient stability of mixed Three-Phase and multi-phase power system were carried out by Tiwari et al.[43] and Auguglario at al. [41] respectively.

Load flow Analysis:-

While Guyker et al.[10] have carried out the load flow study for several cases with the line operating alternatively as Three-Phase and six phase lines, Venkata et al.[9] have carried out such studies on Three-Phase double circuit and Six-Phase line. An extensive investigation as well as analysis of load flow was carried out by Tiwari et al. [43, 83]. Various alternative schemes for such studies depending upon the nature and the point of interest of investigation in Six-Phase or Three-Phase or both parts of the network were presented for balanced as well as unbalanced situations. Further, several case studies together with the impact of converting Double Circuit Three-Phase lines to Six-Phase lines were carried out.

Fault Analysis:-

Enough work has been reported in the area of fault analysis which is one of the important aspects of transmission planning and design activity. The analysis of faults in Six-Phase transmission system was carried out by several authors employing symmetrical component transformation [17, 44], Clerke's component transformation [22] and alpha, beta, zero components [23]. In these studies [17, 21, 23, 44], the major important efforts have been directed to explain the procedure by drawing sequence networks for each case of faults for conceptual clarity. Onogi et al. [45] have carried out fault analysis of Six-Phase system with the help of combined use of Twelve-Phase and Six-Phase symmetrical components method. The study has presented interesting methods of suppressing the fault current. Further, the methods were modified [46] for limiting the line to ground fault and short circuit currents without causing noticeable fall in unfaulted voltages.

Venkata et al. [47] have studied the various types of faults and their combination in an extensive manner for 138 KV Six-Phase line. The analytical expressions for all 23 types of faults and the techniques for evaluating the source impedances at the two ends of the transmission line were developed. The bus impedance formulation of fault analysis of Six-Phase transmission lines employing symmetrical component transformation was presented by Tiwari et al [33]. All significant combinations to ground short circuits of Six-Phase line connected to Three-Phase network via wye / star transformers at both ends employing phase coordinate method were investigated. Gross et al [49] have presented a systematic general method for calculating phase sequence voltages and currents throughout a power system of mixed phase order subjected to an arbitrary fault type at an arbitrary bus in the system. This procedure was amply demonstrated through illustrative calculations carried out on a power system network. The fault analysis of Six-Phase transmission system was carried out by several authors employing generalized treatments [50-54] involving both transformation techniques and phase coordinates.

Bhatt et al. [53] presented a general treatment of phase faults on Six-Phase generators. Another method was also developed [54] to analyse simultaneous ground faults on Six-Phase power system. The several methods to reveal sequence networks due to these faults were discussed. Faults on Nine-Phase and Twelve-Phase systems have been analysed by solving each fault separately. Voltage and current expressions for different faults on both systems with corresponding sequence networks were presented by, Shukla et al [55] and Pal et al. [56] respectively.

Moran [57] has analysed certain series faults in Six-Phase electric power system. Five cases of faults were considered using Fortescue transformation. Expressions for fault currents, voltages (both in sequence components and phase variables) and the connection of sequence network in each case were also presented.

Line protection:-

The protection of 138 KV Six-Phase transmission system against faults and over voltages was studied by Guyker et al. [10, 58]. It was reported that twenty one distance relays were needed to completely protect a Six-Phase line. The connection for percentage differential relay for a delta-star Three-Phase / Six-Phase transformer was shown. Chandra et al. [59] proposed an ultra high speed relaying scheme based on the concept of traveling waves. For this purpose, the frequency domain technique for modeling the Six-Phase line was presented.

Transient Stability:-

Enough work has also been reported in the area of transient stability. Tiwari et al. [60] have carried out a transient stability analysis on Six-Phase power system. For this purpose, an equivalent Single-Phase and the Phase Co-ordinate representation of transmission networks were employed to simulate transient stability behavior of complete Six-Phase system as well as a composite Three-Phase / Six-Phase system. A generalized procedure to analyse transient stability for symmetrical and asymmetrical faults in mixed Three-Phase and Six-Phase power systems based on the symmetrical component method was presented by Augugliaro et al. [41]. Expressions for fault admittance for the various types of asymmetrical faults at Three-Phase and Six-Phase lines were derived. The transient stability has been further investigated by Chaudhary et al. [61], wherein, the analysis has been carried out for different power system configurations especially with a view to studying the impact of converting a double circuit Three-Phase line to Six-Phase circuit. Chandrasekaran et al. [24] have also presented a study on stability aspect of Six-Phase system having the critical clearing angle under fault which was calculated using Byrd and Pritchard's formulae.

Network Switching Transient Studies:-

Several transient network analyzer studies on Six-Phase and Twelve-Phase systems are reported to have been carried out by Wilson et al [62], who summarized the specific system configurations; studied maximum voltage surge magnitudes, and observed the effect of line parameters (phase to ground RMS voltage, line length, surge impedance, switching operation and circuit breaker preinsertion resistors etc.). Further, the transient recovery voltages associated with capacitance switching on 138 KV Six-Phase transmission lines have been studied by Ramaswamy et al. [63], deriving analytical expressions for the transient recovery voltages. Venkata et al. [65] developed a generalized computer programme for simulating electrical parameters and performance characteristics of Three-Phase lines. A Six-Phase transmission line simulator has been developed by Chinnarao et al. [66] to carry out several studies on Six-Phase transmission system.

Experimental Line and Circuit Uprating studies:-

The construction and testing of experimental Six-Phase and Twelve-Phase lines have been carried out by Power Technologies Inc. USA. Adequate data; experimental results; design criteria of multi-phase lines; substations; insulators etc. have been described in Ref. [30, 67, and 68]. Allegheny power Company USA in association with the West Virginia University have conducted studies on converting 138 KV double circuit Three-Phase lines to Six-Phase and their findings have been reported in Ref[10]. Central Power Research Institute (CPRI), Bangalore (India) [13] has undertaken certain preliminary studies of examining feasibility of converting certain 220 KV and 400 KV double circuit Three-Phase lines to Six-Phase operation.

Electrical and Mechanical Characteristics and Line Design:-

The steady state characteristics of a six phase transmission line viz. voltage gradient on conductor surface, electric field intensity on the ground level, and space distribution of energy were investigated by Takasaki et al.[69]. A comparative study between Three-Phase double circuit and Six-Phase lines with different phase arrangements has also been carried out [69]. Grant et al. [70] have carried out comprehensive studies of Mechanical and Electrical characteristics of EHV multi-phase lines. In their studies they have compared the Mechanical and Electrical characteristics of 462 KV Six-Phase and Twelve-Phase lines with similar power transfer capability to that of a 1200 KV Three-Phase line.

Economic viability Analysis:-

An economic optimization study has been made by Stewart et al. [71] considering five alternative multi-phase transmission schemes under the assumption of specific technical and economic parameters. The study has shown clear economic viability of multi-phase schemes arriving at a conclusion that the overall cost reduces with the multi-phase systems. Kallaur et al [72] have further investigated and found that the Six-Phase line is an economic uprating tool for double circuit three-phase lines.

Multi-phase Machines:-

Because of potential benefits resulting from a multi-phase system, some interest has recently grown in the area of multi-phase machines, although the concept of using phase order more than three was experimented in the past. Holley et al.[73] and Hanna et al.[74,75] described the use of Six-Phase generator and its associated transformer for high power applications. Schiferi et al. [76,77] experimented Six-Phase synchronous machines with ac and dc stator connections for an equivalent circuit, carried out steady state as well as harmonic analyses. The characteristics of several high phase order induction motors were examined by Klingshirm [78, 79]. Tiwari et al. [31], Choudhary et al. [80,81] and Gabar et al.[82] have presented mathematical modeling for steady state analysis, dynamic stability, transient analysis, and inherent symmetries of a Six-Phase synchronous generator.

The Effectiveness of Series Capacitor in multi-phase transmission line:-

The effectiveness of series capacitor in long distance Three-Phase has been seen so far, but here, an attempt is made for the first time to visualize the effect of series capacitor on Multi-Phase transmission lines. When series capacitor is inserted in the transmission line, the reduction of the transfer impedance of the line will generally be less than the capacitive reactance of the series capacitor. This discrepancy was first referred to by Janeke and Akerstorm [132] in 1952, but it was not analysed in detail. The difference is explained in the present work in terms of new index called "Compensation Efficiency".

Further, the effects of capacitor location, the Degree of Compensation and its distribution along the line on compensation efficiency are fully analysed. Analytical expressions for the determination of the Compensation Efficiency for various cases are derived. The shunt compensation which is normally used for limiting over-voltages, is shown to behave in a peculiar manner on series compensated line. Normally the stability limit decreases with the shunt compensation. However, on a series compensated line it is shown that there can be other possibilities. The stability limit is shown to have improved when the shunt compensation is above critical value. An analytical expression has also been derived for critical shunt compensation.

This behavior of the shunt reactor on a series compensated line has a marked influence on the nature of switching of the network for optimum control of electromechanical oscillations. The necessary theoretical background of network switching for suppression of electromechanical oscillations was first suggested by O.J.M. Smith [135] and Mittle el. Stadt W.A. et al. [134]. In this, the necessary modification of the switching scheme and an extension of the theory of coordinated control are presented. It is general concept that series capacitors can result in self excitation and dynamic instability of synchronous machines. But, it is shown here that for normal degrees of series and shunt compensation, these two problems are not encountered. Further, it is shown that when long unloaded transmission line is energized by the synchronous machine, both series and shunt capacitors help in preventing possible self excitation.

1.3 Motivation:

In view of the continual growth in power generation, trends towards large unit plant capacity remotely located power plants and necessity of interconnecting them to have maximum benefits from diversity and reserves etc.; the transmission systems have become of greater importance and concern in modern electric power system. Electric utilities all over the world are faced with the pressing need for increasing transmission capacity of their lines, to cater to an ever increasing demand for electricity.

The optimization of existing transmission facilities; minimizing right of way as well as losses in the lines are now being recognized as the basic necessities for planning and design exercises. On the other hand, the transmission of bulk power has necessitated refinements of design of transmission systems as well as the search for better alternatives. The most common solution sought for increasing transmission capability of A.C. transmission by enhancement of system voltage. The enhancement of voltage level has by now reached to such an extent that it poses several technical and environmental problems, making it imperative to use prohibitive sizes of transmission structures and corridors.

Consequently, the search and improvement of all viable transmission alternatives are now in full swing.

Out of the various transmission alternatives, a multi-phase transmission of electric power has attracted considerable attention in the recent past. The literature is replete with several interesting features of this new technology pointing out the advantages accrued from the use of multi-phase transmission system, the efficient utilization of right of way and the enhanced power capability are, however, the most striking features of the multi-phase lines. Although a considerable research has been made for investigation of multi-phase power transmission systems, greater efforts are still required to be made for modeling as well as analyzing such systems before they are actually planned in practice. It is, therefore, motivated me to set the prime objective of this thesis, as furnished hereunder.

The objective and Scope of the thesis:-

1. To derive and evaluate line parameters of multi-phase transmission systems for both transposed and untransposed situations.

2. To present an overview of the transformers required for Three-Phase to multi-phase conversion.

3. To discuss the developed mathematical models offline and associated components employing phase parameters as well as symmetrical components.

4. To develop the analytical tools for steady state analysis particularly the line Loadability and Loadability dependence on Var supply. (Gujarat Energy Transmission Company's (GETCO'S) 400KV network taken into consideration.)

5. To make comparative design to bring out salient features of performance of multi-phase system as compared to the existing GETCO'S Three-Phase double circuit system.

6. To analyse the effect of compensation on Three-Phase and multi-phase transmission systems as a comparative study, with due regards to the various locations of capacitor banks, and behaviour of shunt compensation on series compensated line.

7. To study the newly defined terms viz., “Compensation Efficiency”; “Critical Compensation”; “Optimum Compensation” for deriving expressions for the various situations.

8. To observe impact of compensation on multi-phase line as compared to Three-Phase double circuit line.

9. To carry out Load flow analysis on a mixed Three-Phase single and Double Circuits, and observe the effect of converting the Three-Phase Double Circuit Lines into Six-Phase on a sample system

10. To simulate Three-Phase Double Circuit System and its conversion into Six-Phase by MATLAB Simulink tool and make a comparative study of the effects of various types of faults at different locations on both the systems.

1.4 Thesis Organization:-

Chapter: 1 INTRODUCTION

This chapter presents motivation and a brief review of the literature on research and development of different aspects of the Multi-Phase transmission systems.

Chapter: 2 EVALUATION OF LINE PARAMETERS

This Chapter is devoted to the analytical developments to study various parameters of Multi-Phase transmission system (particularly Six-Phase) which may lead to the better understanding and modeling of lines of various system studies. Expressions for the

Inductance, Capacitance for Multi-Phase Transmission System are developed covering transposed and untransposed situations, as well as, ground effects and lightening shield wires. Potential and Maxwell coefficients describing Capacitance and Inductance matrices of Multi-Phase Transmission System are developed. Matrix diagonalising transformations for Multi-Phase Transmission System is derived. Several calculations have been carried out on different conductor configurations and line geometries to support validation of the expressions derived and also to bring out a comparative view of Multi-Phase Transmission Line Parameters with their Three-Phase counterpart.

A comparative statement of the design output for various possible conductor configurations has been prepared keeping in view mainly the existing GETCO'S Three-Phase Double Circuit System (TPDCS). The other configurations selected are such as to effect minimal changes in the existing GETCO'S configuration of Three-Phase Double Circuit. The comparative design output table clarifies the talismanic role of Six-Phase transmission system over its Three-Phase Double Circuit System counterpart.

It will be seen from the comparative design table that, HPOTS have higher Inductance and lower Capacitance i.e. greater SIL capability. For Three Phase Double Circuit System(TPDCS), Power = $2 \times 3V_{ph} I_{ph} \cos\theta$, Where, $V_{phase} = V_{line} / \sqrt{3}$. Whereas, for the Six-Phase System, Power=$6\ V_{ph} I_{ph} \cos\theta$ where, $V_{phase} = V_{line}$ since it forms an equilateral triangle. This fact gives 1.7 to 1.74 times more power than the existing TPDC line depending upon the line configuration. Further it can be stated that, for the same amount of power transfer, if we keep V_{phase} same, it will reduce V_{line} which in turn will also reduce the overall dimension of tower, its foundation cost and also the Right of Way problem. HPOTS can also address the Line Congestion Problem and Transmission Pricing Problem during the Peak Load Condition in deregulated environment. For the same amount of power transfer, Six-Phase conversion gives better regulation as it has got higher SIL. However, if six-phase conversion is made for more amount of power transfer, it gives a bit poor regulation which can be well addressed with the available FACTs devices.

The disadvantage of HPOTS is that the terminal expenses are higher than those of the TPDC System as HPOTS would require specially built transformers at both the ends of the transmission line. The increased cost is, however, offset by the reduced tower size, its foundation cost, Right of Way cost, enabling us at the same time to alleviate the adverse biological effects. This aspect of compact line structure makes HPOTS an attractive & potential alternative in planning as well as in embarking upon an entirely new venture for bulk power transmission both at EHV and UHV levels

Chapter: 3 MODELLING OF ELEMENTS OF MULTI-PHASE TRANSMISSION NETWORK

This Chapter starts with an overview of some transformers required for Three-Phase to Multi-Phase conversion. Suitable mathematical models for Three-Phase/ Six-Phase and loads are discussed. The Phase Co-ordinates as well as the Symmetrical Component representations for analyzing a composite system of Three-Phase and Multi-Phase, ABCD parameters and Three-Phase equivalents of Multi-Phase line are presented. With the help of case study of two alternative transmission systems, certain important characteristics of Multi-Phase lines are obtained to highlight the comparative merits / demerits of Multi-Phase system over corresponding Three-Phase System.

It can be observed from the discussion that the equivalent Three-Phase impedance matrices of Multi-Phase lines resemble balanced Three-Phase lines having no mutual coupling between the phases. The matrices are characterized by lower diagonal and zero mutual impedances. Further, Symmetrical Component transformation of these matrices produces equal sequence impedances. The Six-Phase equivalent impedance matrix of Three-Phase line is a circulant matrix and its non-diagonal elements are not all equal. The Multi-Phase lines are characterized by lower charging currents as compared to their lower phase order counterparts. This lower charging current associated with Multi-Phase lines appears to suggest a reduced Ferranti effect on Multi-Phase lines. As Multi-Phase lines are associated with the lower capacitance and somewhat higher inductance, its behavior would depend upon the line configuration adopted in practice.

Chapter:4 LOADABILITY CHARACTERISTICS OF MULTI -PHASE LINES

Loadability characteristics of Multi-Phase transmission lines have been studied extending the analytical concepts developed over the years for Three-Phase Systems. The procedure to derive Loadability curves and operating Loadability curves are explained. An assessment of the benefits of Multi-Phase lines in terms of their Loadability as constrained by system performance and operating environment criteria, is made with regard to their lower phase order counterparts, and the problem of Loadability dependence on Var supply is studied. The study is carried out on GETCO'S Three-Phase Double Circuit System and its conversion into Six-Phase to highlight the benefits of Multi-Phase lines as well as their deployment for circuit uprating of the conventional Three-Phase Double Circuit system. The salient points from the loadability study are furnished hereunder, employing the same operating criteria of 30% Steady State Stability margin and 5% Voltage drop on both TPDCS and the Six-Phase System. The same Line Configuration, Line to Line Voltage, and Line Length, were considered for the comparative study of Loadability on both the systems.

From the loadability study, we can state that for uprating the TPDC line to Six-Phase line, the adjacent line to line voltages should remain the same with assumption that conductor currents and power factors in both the modes of operation are also the same. During the course of study, it is further verified that the Six-Phase operation is equivalent to a TPDC line uprated to √3 times its line voltage, so far as the loadability is concerned. It is also observed that the Compensation required for the same margin of increase in the loadability is less in the case of Six-Phase than that of the TPDC system, viz. Var required will be less in Six-Phase system than that in TPDC system. Six-Phase line offers more power transfer for the same performance criteria (voltage limit and stability margin) as compared to TPDC system. The Shunt Compensation has a negligible effect on line loadability while the Series Compensation has more pronounced effect on line loadability. Six-Phase line has better voltage performance and better stability margin especially during heavy load region, as compared to its TPDCS counter-part. Six-Phase up-rating of TPDC line yields around 75% benefit in line loadability.

Chapter: 5 EFFECTIVENESS OF SERIES AND SHUNT COMPENSATION ON MULTI-PHASE TRANSMISSION LINES

The effectiveness of series capacitor in long distance Three-Phase and Multi-Phase transmission lines is analyzed. When series capacitor is inserted in the transmission line, the reduction of the transfer impedance of the line will be generally less than capacitive reactance of the series capacitor. This discrepancy was first referred to by Janeke and Akerstorm [132] in 1952, but it was not analyzed in detail. The difference is explained in the present work in term of new index called "Compensation Efficiency". Further, the effects of capacitor location, the Degree of Compensation and distribution of Capacitor Bank along the line on Compensation Efficiency, are fully analyzed. Analytical expressions for the determination of the Compensation Efficiency for various cases are derived. The shunt compensation which is normally used for limiting over voltages is shown to behave in a peculiar manner on series compensated line. Normally the stability limit decreases with the shunt compensation. But on a series compensated line it is shown that there can be other possibilities. The stability limit is shown to have improved if the shunt compensation is above critical value. An analytical expression has also been derived for critical shunt compensation.

It is observed from the Compensation study on both Multi-Phase and TPDCS that the net transfer reactance is not just the arithmetical difference between the total inductive reactance and capacitive reactance of series capacitor but, it (net transfer reactance) depends on Degree of Series Compensation; location of the compensation bank along the line; the line length; and the number of series capacitor banks over which series compensation is distributed. For the longer lines, the resultant transfer reactance will be more due to the line charging effect. In order to account for this discrepancy, the term "Compensation Efficiency" is introduced to indicate the effectiveness of the series capacitor bank(s) in reducing the transfer impedance. The Compensation Efficiency (K) is defined as the ratio of the net reduction of transfer reactance to the reactance of the series capacitor bank used. It can be mathematically proved that the Transfer impedance is minimum when the Series Capacitor Bank is located at the center of the line, but the effect of line resistance shifts optimum location of the Capacitor Bank slightly towards the receiving end. The effectiveness of the series compensation decreases with the increasing line length. However, with the higher order of transmission this effectiveness increases for an equal amount of increase in power transfer. It is, however, found that at low degrees of Series Compensation, Compensating Efficiency with Two Capacitor Banks is slightly less than that obtained with a Single Capacitor Bank. This, in fact, is the reason for the requirement of higher MVAR rating for two capacitor banks at one-third points along the line than for one capacitor bank at the mid-point. It is, however, noticed that beyond the critical shunt compensation value, the compensation efficiency increases, and thereby the power transfer capability also increases. The value of the critical shunt compensation (b_{cr}) is just the value of shunt compensation beyond which the transfer impedance of the line starts decreasing from the value corresponding to zero shunt compensation. The term, "optimum shunt compensation (b_{opt})" It is at this point that the transfer impedance changes the direction of its variation. The compensation efficiency decreases considerably with the increase in shunt compensation, when the capacitor bank is located in the vicinity of the mid point of the line. However, at higher values of series compensation the effect of shunt compensation tends to increase the compensation efficiency for all positions of the series capacitor bank. The effect of shunt compensation in reducing the Ferranti over-voltage is predominant only when it is placed at the receiving end of the transmission line. For other locations, the series capacitor itself reduces the power frequency over-voltages considerably.

Chapter: 6 COMPARATIVE LOAD FLOW STUDY

A sample system is taken into consideration with 6 buses, 8 lines. Out of these 8 lines, the lines which are Three-Phase Double Circuit in nature (Lines 6,7 & 8) are transformed into Six-Phase, and the load flow analysis is done on both the networks to visualize the effect of Six-Phase conversion on load flow results. The results obtained are tabulated for the various cases to highlight the effectiveness of the Six-Phase transformation of the existing Three-Phase Double Circuit lines.

Before performing the Load Flow Analysis on a sample system, it is imperative to briefly outline the Mathematical Modelling of the Transmission Lines with a view to providing a quick reference to readers.

It has been observed from the Load-Flow Study of a sample system that the voltage magnitude and phase angles of all nodes improve substantially when the lines 6, 7 & 8 are converted into Six-Phase lines, maintaining the same line voltages and conductor configuration. Even with the increased loading of 1.67 times (than that of the original system load) on the Sample System (in which Three-Phase Double Circuit Lines are converted into Six-Phase Lines), the benefit of the improved voltage magnitudes and phase angles are retained to an appreciable extent, as evident from the values for P,Q at nodes. This confirms that the better voltage regulation or MVAR control is obtained by replacing TPDC line by Six-Phase. The real and reactive power loading of most of the lines are reduced. The benefit is relatively more quantitative in reactive power flows. The improvement in line efficiencies means the reduced line loss in the system. The lines 6, 7 & 8 retain marked efficiencies in all cases. The system can transfer more load - a phenomenon that has been checked by increasing the system load from 759.70 MW to 1261.70 MW (1.67 times the original loading) by providing additional generating capacity at node 3 and at node 6. The data and results are tabulated. It is evident from the results that the system load can be increased without overloading any of the lines, and at the same time maintaining appreciable benefit in voltage regulation and efficiencies.

Chapter: 7 FAULT ANALYSIS OF THE THREE-PHASE DOUBLE CIRCUIT SYSTEM AND THE SIX-PHASE SYSTEM.

The MATLAB simulation has been done for the GETCO's 400KV TPDCS line and its conversion into Six-Phase. The phase conversion is made on the principle that 2-Three-Phase Supplies are displaced by 180^0 and superimposed on each other to form Six-Phase. The Six-Phase conversion is made by using two 12-terminals Three-Phase transformers, (*Because in MATLAB transformers with tappings are not available, otherwise one may use a Single transformer with centre taps on each phase to form two Three-Phase systems being displaced by* 180^0 *to avail Six-Phase power out of Three-Phase supply.*) For the simulation of various faults at different locations, two distributed parameters blocks are kept, and line length of an individual block is varied to create fault at the desired location. On the receiving end, the same pair of transformers in mirror fashion is used for Six-phase to Three-Phase conversion. The graphs of fault currents and phase voltages are obtained for various faults at different locations for the same amount of load on both the systems. The simulation is done with **ode15s** simulation tool. The selected graphs have been furnished for the readers' perusal.

The observation of the simulation results and graph reveals that the magnitude of fault current is less for the 6-phase system than that for the TPDCS with the same fault resistance, fault type and fault location. It is also observed that 3-phase to ground fault is the most severe fault in the case of the TPDCS. Similarly, Four-phase to ground fault is the most severe fault in the case of the Six-Phase system. The Line regulation is better in the Six-Phase System as compared to that of the TPDCS. The curves plotted for the load voltages for line to ground fault on Mid-point of transmission line show significantly less distortion in the case of the Six-Phase system as compared to that of the TPDCS.

Chapter: 8 CONCLUSIONS

This Chapter consolidates the important findings and brief review of the work reported in the thesis. The future scope and the further investigations in this area are highlighted. This is followed by Appendix A, B, & C furnishing the important theories, algorithms, derivations, etc. for the perusal of readers.