CHAPTER – 1

INTRODUCTION

1.1 The Problem of Transient Stability :

Since the early days of a.c. power generation and utilization, power systems rely on synchronous machines for generation of electrical power. Initially, power systems were of isolated nature having individual generators or power plants supplying their own local loads. As time progressed, the power systems grew in size and complexity with large distances between various generating plants and load areas. To meet the growing demand reliably and economically, distant regions were interconnected electrically. The modern transmission systems are complex networks of transmission lines interconnecting many generating stations and major loading points in the power systems. For satisfactory operation, it is a fundamental requirement that all synchronous machines in the system operate in synchronism, a condition which is fulfilled when the rotor of all machines maintain a common angular speed or frequency

Power systems are exposed to various dynamic disturbances, large (such as line or equipment faults , various switching operations) or small (normal load switching) which may result in a sudden change in the real power balance of the system, and consequently acceleration and decelerations of different degrees of different machines, causing oscillations between them. Ever since the machines of a power system were interconnected, mechanical oscillations between their rotors have been known to be present. These oscillations are influenced by the power flows between the machines. These power flows are dependent on the relative positions of the rotors of the interconnected machines and given by the following non-linear relation (e.g. between the ith and jth machines)

$$P_{ij} = E_i E_j Y_{ij} \sin(\delta_i - \delta_j - \alpha_{ij}) \qquad (1.1)$$

where

P_{ij} is the active power flowing from the ith machine to the j th machine.

E_i and E_j are the internal voltage magnitudes of the i th and the jth machine respectively.

δ_i & δ_j are the rotor angular positions of the respective machines referred to a common axis.

$Y_{ij} \angle -\theta_{ij}$ is the transfer admittance between the two internal voltages E_i & E_j.

$\alpha_{ij} = (90- \theta_{ij})$

In an n-machine power system, rotor oscillations of the ith machine can be described by the following 2nd order differential equation :

$$M_i \ddot{\delta}_i = P_{mi} - P_{ei} \qquad (1.2)$$

where

M_i is the inertia constant of the ith machine

P_{mi} is the mechanical input power of the ith machine.

P_{ei} is the electrical power devopled by the ith machine

δ_i is the rotor angle of the ith machine with respect to a synchronous rotating frame.

The above equation is non-linear beacause

$$P_{ei} = E_i^2 G_{ii} + \sum_{\substack{j=1 \\ \neq i}}^{n} E_i E_j Y_{ij} \sin\left(\delta_i - \delta_j - \alpha_{ij}\right) \qquad (1.3)$$

is a nonlinear function of δi.

In equation (1.2) P_{mi} exerts accelerating or driving force and P_{ei} exerts a braking force on the rotor of the i th machine. Steady state is a condition of equilibrium between these two opposing forces. Under steady state condition, such equillibrium exists for each machine, and the speed remain constant at a value (known as synchronous speed) corresponding to the rated system frequency.

But a real power system is never truly in the steady state since there are always disturbances of small or large size which cause the system to be continually adjusting to meet new conditions. The mechanism by which interconnected synchronous machines maintain synchronism with one another is through restoring forces (also known as synchronising power) which act whenever there are forces tending to accelerate or decelerate one or more machines with respect to the others. If one generator temporarily runs faster than another, the angular position of its rotor relative to that of the slower machine will advance, resulting in larger power transfer from the advanced machine to the other. Alternatively, one can say that the slower machine transfers part of its load to the advancing machine. This tends to reduce the speed difference and hence the angular separation between them. Whether the angular separation goes on increasing in an unbounded manner or starts reducing after attaining a certain peak is attributed to the property called stability of a power system which may be defined as the ability of the system to remain in synchronism after being subjected to a disturbance. Transient stability (also referred to as first swing stability) refers to that ability following a major disturbance such as short circuit on transmission lines , loss of generating unit or large load etc.

1.2 Factors Affecting Transient Stability :

Transient stability of a power system is determined by the transient stability of its interconnected generators. Transient stability of a generator is dependent on the following factors:

(i) Prefault loading of the generator .

(ii) The generator output during the fault.

(iii) The fault clearing time.

(iv) The post-fault network configuration.

(v) The generator reactance.

(vi) The generator inertia.

(vii) The generator internal voltage magnitude.

During a fault, such as a short circuit on a transmission line, the outputs of the generators in a power system drop usually to very low values. As the mechanical nputs to the generators remain almost constant during the period of fault, the generators accelerate and gain kinetic anergy (K.E.) due to the accelerating power resulting from the power imbalance. From the equal-area criterion [1] or from the energy- integral criterion [2,3] it is understood that more is the K.E. gained by a generator during a fault, greater is the chance of its loosing transient stability.

Factors (i),(ii),(iii) and (vi) influence the K.E. gained by the machine rotors during the fault period.. Heavier loading of a generator means higher mechanical input to it. The electrical output of a generator during a fault depends on the location, type and severity of the fault. Heavier prefault loading and lower output during fault will cause higher acceleration and, therefore, higher K.E. gained by the generator during fault. Rapid clearing of a fault reduces the K.E. gained by a generator for a certain pre-fault loading and a certain fault. The higher the inertia, the slower the rate of change in rotor angle of generator. This reduces the K.E. gained during fault.

Factors (iv), (v) and (vii) determine the synchronising power between the generators during the post-fault period. (iv) and (v) determine the transfer admittance between the generators. Higher value of transfer admittance and higher internal voltage magnitudes (factor vii) increases the synchronizing power, and hence results in greater transient stability.

1.3 The problem of Transient Stability Control :

Growing demand for economical power has compelled the power system operators to run the systems with heavily loaded lines transmitting large blocks of power over long distances. The quest for economy has resulted in the reduction of transient stability margin of power systems. This necessitated additional control actions for augmenting transient stability margin. Such control allows the power systems to operate with more heavily loaded lines and still be able to withstand severe system disturbances which, otherwise, would render the system transiently unstable.

Although the main aim of transient stability control is to maintain the first swing stability, it is also essential that the control actions should provide sufficient damping to reduce the subsequent oscillations so that smooth transition to the post-fault equilibrium is ensured. The control strategy for this purpose should be able to suitably modify the parameters of the swing equation (1.2) so that an otherwise unstable response becomes stable in the presence of control. In the swing equation the controlable parameters are [4] P_{mi}, E_i, G_{ii} and Y_{ij} . In general, the control options available for normal operation of power systems, have relatively long time responses and are unable to prevent transient instability. Special control means are, therefore, necessary for transient stability enhancement. To achieve the required rate of change of parameter values, several methods such as dynamic braking, rapid field forcing, steam turbine fast valving and network switching have been developed. Various control strategies employing these methods have been reported in the literature. These methods have their own merits and limitations. A comprehensive survey and review of them are available in [5 – 7] .

In recent years, alongwith the progress in the field of high power electronics, a new concept- Flexible AC Transmission Systems (FACTS) [8,9] has been introduced to provide much greater control speed and flexibility in the area of power transmission control. The collective acronym FACTS applies to a wide range of large power electronics based controllers, which may be used to make the power systems more flexible and controllable. Employment of various FACTS devices can provide new ways for dynamically adjusting the network configuration and parameters to enhance not only steady state performance but also the transient stability of a power system. Application of FACTS devices for the enhancement of power system transient stability has been the main area of interest to many power system researchers in recent times and results of these investigations have been reported [10-13] in the literature.

Although there have been some successes in the area of transient stability enhancement, several important issues are still challenging control and power engineers and researchers. These include highly nonlinear nature of power systems , decentralized control structure and robustness of control. Power system dynamics are characterized by nonlinear differential equations. Conventional controllers based on linear control theory are designed on the basis of approximate system models linearized around a certain operating point.These controllers can produce satisfactory performance only for small disturbances when the dynamic variables undergo small changes around that particular operating point. Such controllers are, therefore, not suitable when the dynamic variables experience large excursions during the regime of transient stability control. For transient stability improvement, controllers should be designed retaining the nonlinear nature of the system. In other words, the controller should be based on the nonlinear dynamic model and not on the linearized version. This renders the very rich and powerful linear control theory ineffective for such control design, and demands the application of nonlinear control theory.

In the last two decades there have been remarkable advancement in the development of nonlinear control theory and techniques. Methods for nonlinear controller design that are independent of the system operating point have been developed. Among these promising methods, Feedback Linearizing Control (FLC) [30-32] has drawn much attention of the powersystem engineers and researchers. FLC is concerned with the establishment of a nonlinear feedback in a way such that the closed loop system acts as a linear one. In contrast to the local linearization around a certain operating point, feedback linearization is a global transformation in the sense that the resulting linear model is valid for the whole range of the operating points.The main advantage of FLC lies in the fact that once the linearized model is extracted , any suitable method from linear control theory can be applied. In spite of having such attractive features , FLC suffers from some serious drawbacks that must be overcome to apply it in practical field. Firstly, the original system model must be feedback linearizable, and the linearizing transformation must be invertible, at least within the range of operating conditions of interest, so that the original control law can be derived from that determined (usually by some linear control theory) from the linearized model. Secondly, the proper implementation of FLC requires exact cancellation of nonlinear terms by feedback signals. This requires very accurate models incorporating all the necessary details and also the knowledge of all the necessary parameters with reasonable accuracy. However, in practical situation it may not be possible to use a detailed model either due to lack of complete knowledge about the system or due to the fact that such a complex model may be too difficult for further mathematical treatment. Some of the parameters describing the complex model may also be difficult to measure or assess with any degree of certainty or accuracy. Errrors and uncertainties arising due to such model simplification and unavailability of accurate parameter values challenge the robustness of FLC which must be considered while designing a practical controller. A power system, in particular following a major disturbance, behaves as a highly nonlinear uncertain dynamical system. Hence the above mentioned factors should be properly taken into account while designing a feedback linearizing controller for transient stability improvement.

1.4 Developments on Nonlinear Excitation Controller Design :

It is well known that excitation control of synchronous generators is one of the most cost effective ways to enhance the stability of power systems [46]. Enhancing the performance of existing equipments such as excitation systems of generators can add to the reduction of costs involved in installing new devices such as FACTS controllers. Recently FLC methodology has been applied by a number of power system researchers [38- 40] in the design of nonlinear excitation controllers to enhance the transient stability of power systems. Robustness issues associated with these controllers have also been addressed by a number of researchers [41-45]. Although these approaches look very promising, some important factors regarding their physical realization need to be thought over.

1.5 The Unified Power Flow Controller and its potential as a tool for transient stability improvement :

The power transmitted over an ac transmission line is a function of the line impedance, the magnitude of sending-end and receiving-end voltages, and the phase angle between these voltages. Conventional methods of altering these parameters to achieve power transmission control provide adequate control under steady-state and slowly changing system conditions, but are largely ineffective in handling dynamic disturbances. The traditional approach to contain dynamic problems is to keep sufficient stability margins. This approach generally results in a significant under utilization of the transmission system.

As a result of economic, environmental and social developments, and recent trends towards power system restructuring, there is an increasing recognition of the necessity to review the traditional power transmission theory and practice, and to develop new concepts that allow the utilization of existing transmission facilities to the maximum extent possible. In the late 1980's the EPRI formulated the vision of the FACTS in which various power electronics based controllers regulate power flow and transmission voltage, and through rapid control action mitigate dynamic disturbances. To this end, electronically controlled, extremely fast controllers have been developed within the overall framework of FACTS. One group of these FACTS controllers employ conventional thyristor-switched capacitors and reactors, and quadrature tap-changing transformers in traditional shunt or series circuit arrangements. The other group, the more advanced one, employ self commutated switching power converters as Synchronous Voltage Sources (SVS), which can internally generate reactive power for, and also exchange real power with, the ac system.The unified Power Flow Controller (UPFC) [8,9,14,15] is a member of this latter family. It is able to control, simultaneously or selectively, all the parameters affecting power flow in a transmission line (i.e. voltage, impedance and phase angle), a capability which is not attainable to any other device (including the other FACTS devices) presently available for transmission system control. Alternatively, it can provide the unique functional capability of independently controlling both the real and the reactive power flow in a transmission line. This basic capability makes the UPFC the most powerful among the FACTS devices. Investigations [14,15] have shown that the UPFC is a very effective tool for dynamic power flow control in a transmission system. As power flow is closely related to the transient stability of power systems, it is quite natural that the UPFC offers a lot of promise in the area of transient stability improvement , and, therefore, has currently drawn much attention of the power system researchers. Number of study results [16-23] have appeared in the literature. Though the success achieved in these initial investigations generate much encouragement, still a lot of work has to be done before the UPFC can be successfully employed for the mitigation of transient stability problem in a power system. The above studies are either based on the so called Single Machine Infinite Bus (SMIB) model or based on other simplified versions of power systems. Studies [16, 17, 23] show the effectiveness of UPFC in enhancing first-swing stability, but these are based on SMIB systems and inadequate dynamic models of generators and UPFC. While generators were represented by classical 2nd order model, UPFC dynamics were not considered. Some authors [18-21] have presented nonlinear and fuzzy control strategies for UPFC to improve transient stability but they have their limitations. Wang et al [22] have used detailed dynamic model of UPFC and they have also addressed the issue of robustness while developing a co-ordinated control of excitation system and UPFC. But their study is also on an SMIB power system. Studies are, therefore, necessary with more realistic multimachine power system to develop a controller that exhibits sufficient robust performance in the real world power system characterized by high degree of uncertainties and highly nonlinear interactions between several operating variables.

1.6 Scope of the Present Work:

This research work addresses the problem of developing robust nonlinear control strategies for transient stability augmentation. Firstly, a robust FLC excitation control strategy is developed. The developed control strategy falls under a particular variety of FLC, namely, direct feed-back linearizing (DFL) control [39, 40]. From practical point of view, existing robust DFL controllers [41 – 45] are based on complicated mathematical treatment. Computationally they are much involved and their physical realization is not straight forward. In contrast, the proposed control strategy is much more straight forward and easy to realize. Effectiveness of the proposed DFL excitation control strategy has been shown by simulation studies with both SMIB and multi machine power system. Next, a co-ordinated excitation and UPFC control strategy has been developed to improve transient stability. By simulation results it has been shown that the co-ordinated control of the proposed DFL excitation controller and UPFC is very effective for transient stability enhancement.

1.7 Organization of the Thesis:

Rest of the thesis is organized in the following way:

The next chapter describes briefly the dynamic models of synchronous machine, excitation system and UPFC used in the simulation studies.

Chapter – 3 discusses the development of the proposed DFL excitation control strategy, and its effectiveness for transientstability enhancement of an SMIB power system is demonstrated by simulation results.

Chapter – 4 contains the discussions and simulation results on the application of the proposed excitation control strategy for transient stability improvement of multi machine power system.

Chapter – 5 describes the control strategy for UPFC and the co-ordinated excitation and UPFC control for transient stability enhancement.

Chapter – 6 draws a conclusion on the present work indicating its merits, drawbacks and scope of further research in this line.

Two appendices, appendix – I and appendix – II, containing some derivations relating chapter – 3 and chapter – 4 respectively, follow chapter – 6.

Lastly a list of references has been furnished under the head - Bibliography.