APPLICATIONS OF FACTS CONTROLLERS IN POWER SYSTEMS FOR ENHANCE THE POWER SYSTEM STABILITY: A STATE-OF-THE-ART

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ABSTRACT

This paper presents a comprehensive review on enhancement of power system stability such as rotor angle stability, frequency stability, and voltage stability by using different FACTS controllers such as TCSC, SVC, SSSC, STATCOM, UPFC, IPFC in an integrated power system networks. Also this paper presents the current status of the research and developments in the field of the power system stability such as rotor angle stability, frequency stability, and voltage stability enhancement by using different FACTS controllers in an integrated power system networks. Authors strongly believe that this survey article will be very much useful to the researchers for finding out the relevant references in the field of enhancement of power system stability by using different FACTS controllers in an integrated power system network.


1. INTRODUCTION

In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded and the power system stability becomes a power transfer-limiting factor. Flexible AC transmission systems (FACTS) controllers have been mainly used for solving various power system steady state control problems. However, recent studies reveal that FACTS controllers could be employed to enhance power system stability in addition to their main function of power flow control. This literature shows an increasing interest in this subject for the last two decades, where the enhancement of power system stability using FACTS controllers in an integrated power system network has been extensively investigated.

Power system stability has been recognized as an important problem for its secure operation since 1920s [1, 2]. Result of the first laboratory tests on miniature systems were reported in 1924 [3]; the first field tests on the stability on a practical power system were conducted in 1925 [4, 5]. Traditionally, the problem of stability has been one of maintaining the synchronous operation of generators operating in parallel, known as rotor angle stability. The problem of rotor angle stability is well understood and presented in literatures [6]-[10]. With continuous increase in power demand, and due to limited expansion of transmission systems, modern power system networks are being operated under highly stressed conditions. This has imposed the threat of maintaining the required bus voltage, and thus the systems have been facing voltage instability problem [11]-[13]. Due to increase in power demand, modern power system networks are being operated under highly stressed conditions. This has resulted into the difficulty in meeting reactive power requirement, especially under contingencies, and hence maintaining the bus voltage within acceptable limits. Voltage instability in the system, generally, occurs in the form of a progressive decay in
voltage magnitude at some of the buses. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and other elements by their protective systems leading to cascaded outages and voltage collapse in the system [13, 14]. Voltage collapse is the process by which the sequence of events, accompanying voltage instability, leads to a blackout or abnormally low voltages in a significant part of a power system [10, 15, 16].

In this work, the current status of power system stability enhancement by using FACTS controllers was discussed and reviewed. This paper is organized as follows: Section II discusses the definitions and dynamic phenomena regarding with power system stability. Section III introduces the shortcoming of a literature survey. Section IV introduces the review on improvement of power system stability by placement and coordination of FACTS controllers in an integrated power system networks. Section V presents the results and discussion of the paper. Section VI presents the conclusions of the paper.

2. MATHEMATICAL MODELING OF AN INTEGRATED POWER SYSTEM NETWORKS FOR ENHANCEMENT OF POWER SYSTEM STABILITY VIEWPOINT

"Safe operation of electric power system is largely related to its stability which depends of the ability in making all generators supplying the network rotate synchronously despite faults and other contingencies. Stability of general dynamical systems and more specific definitions for power systems are introduced in the chapter. Dynamical phenomena in power systems along with main causes of in-stability and their underlying phenomena are briefly described".

Electric power systems are constituted by the interconnection of a huge number of different components. They can therefore be considered among the most complex systems to be planned and safely operated. This complexity arises as a consequence of the large amount of devices contemporaneously in operation, each one with its own internal dynamics, that however interact with each other, giving rise to a complex collective behavior. The wide geographic extension of electric power systems that can span entire countries and even continents, adds even greater complexity to issues connected to their analysis and control.

During their operation power systems undergo a large number of disturbances, some of them occurring continually, such as modifications in load demands, while others are less common but nonetheless can potentially be very dangerous, such as faults and structural changes like tripping of circuit breaker. From a practical viewpoint such disturbances are usually classified as either small or large, respectively, depending on the effects they have on system behavior. Just like any other dynamical system, the most basic requirement related to power system secure operation is therefore its stability.

Although several mathematical definitions have been proposed for generic dynamical systems, and most of them can be usefully applied to power systems too, the need for more practical definitions have led joint IEEE/CIGRE Task Forces to propose commonly agreed definitions [10,16]. Quoting from [10]:

"Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact."

Under very general assumptions the dynamics of power systems can be described by a switched set of coupled algebraic and ordinary differential equations of the form [6]:

\[ x = f_i(x, y, t) \]

(1)

\[ 0 = g_i(x, y, t), i \in \{e_1, \ldots, e_k\} \]

(2)

The index \( i \) spans over a discrete set of possible events that make the system change its intrinsic dynamics, at specified time instants. State variables \( x \) are not allowed to change instantaneously following an event, while algebraic variables \( y \), which are defined by equation (2) as implicit function of the state variables \( x \), can undergo discontinuities. Systems of this kind fall into the wide category of hybrid systems, i.e. systems in which continuous dynamics co-exists with discrete events. A more detailed description of such hybrid systems along with a more formal mathematical framework suitable for their application to the description of power systems is presented in [17]. Examples of discrete events that can trigger a structural change in system's dynamics are faults,
tripping or reclosure of a transmission line, load shedding and under load changer action. 
Due to the explicit dependence on time of right-hand sides of equations (1-2) the system is said to be non-autonomous. 
In the foregoing discussion it is assumed that the hypotheses of the implicit function theorem are satisfied. In particular the Jacobian of $g$ with respect to $y$ is supposed to verify:

$$\det \left( \frac{\partial g(x, y)}{\partial y} \right) \neq 0$$

(3)

which guarantees that there exist a function $h(x)$ such that the algebraic variables can be expressed as $y = h(x)$, therefore the differential-algebraic equations (DAE) (1)-(2) can be replaced by:

$$x = f(x, h(x))$$

(4)

A typical power system stability study considers the system to be in a pre-disturbance steady state, mathematically described by [18]:

$$x = x_{\text{prefault}}^*$$

(5)

$$0 = f_{\text{prefault}}(x, y, t)$$

(6)

$$0 = g_{\text{prefault}}(x, y, t), \forall t \leq t_{\text{fault}}$$

(7)

where $x_{\text{prefault}}^*$ is the pre-fault equilibrium point, and $t_{\text{fault}}$ is the time instant when fault happens. During the fault, most often a short circuit at some network location, system's dynamics are described by:

$$0 = f_{\text{fault}}(x, y, t)$$

(8)

$$0 = g_{\text{fault}}(x, y, t), \forall t_{\text{fault}} \leq t \leq t_{\text{fault}} + t_{\text{cl}}$$

(9)

where $t_{\text{cl}}$ is the fault clearing time. Studying system's stability is thus the question of whether post-fault state variables reach a new acceptable equilibrium point or not. The post-fault equilibrium point $x_{\text{postfault}}^*$ can either be the same as pre-fault equilibrium or differ from it. Analogously, post-fault dynamics can either be the same as pre-fault dynamics, in which case $f_{\text{postfault}}(x) = f_{\text{prefault}}(x)$ or differ from it, i.e. $f_{\text{postfault}}(x) \neq f_{\text{prefault}}(x)$, depending on the event of structural changes following the intervention of protective equipment, like line tripping or load shedding. The aforementioned definition from does not explicitly mention equilibrium points in order to allow for the possibility that satisfactory operation can also be attained while some state variables remain on a limit cycle, thus never reaching a true equilibrium point, but still remaining limited within an acceptable region. This possibility is however not commonly encountered in actual power system operation, since small parameter variations can either transform stable limit cycles into unstable ones or into stable equilibrium points.

3. ANALYSIS OF POWER SYSTEM STABILITY IN AN INTEGRATED POWER SYSTEM NETWORKS BY USING LYAPUNOV’S STABILITY THEORY

A. Mathematical Definitions:

For a given dynamical system described by the set of first order ordinary differential equations

$$x = f(x),$$

the following definition holds:

**Equilibrium point:** If:

$$\forall \varepsilon > 0, \exists \delta > 0, \forall t \geq t_o \Rightarrow x(t) = x^*, \forall t \geq t_o$$

(10)

than the state $x^*$ is said to be an equilibrium point. Which means that the system is in an equilibrium state if once $x(t)$ is equal to $x^*$ it remains $x(t) = x^*$ for all subsequent time. From this condition it follows that:

$$x^* \text{ is an equilibrium point } \iff f(x^*) = 0$$

(11)

The definitions of stability for an equilibrium point of the generic system $x = f(x)$ can be formalised using the classical definition by Lyapunov’s [18, 19, 20]:

**Stability:** The equilibrium point $x = 0$ is said to be stable if:

$$\forall \varepsilon > 0, \forall t_o \geq 0, \exists \delta(t_o, \varepsilon), \| x(t_o) \| < \varepsilon , \Rightarrow \| x(t) \| < \varepsilon, \forall t \geq t_o$$

(12)

Also figures 1 explain the definitions of stability.
Roughly stated, the definition implies that trajectories initiating sufficiently close to the equilibrium point will eventually remain in its neighborhood. If \( \delta(t_o, \epsilon) \) can be chosen independent of \( t_o \), uniform stability holds according to the following definition:

**Uniform stability**: The equilibrium point \( x = 0 \) is said to be uniformly stable if:

\[
\forall \epsilon > 0, \forall t_o > 0, \exists \delta(\epsilon) :
\| x(t) \| < \epsilon, \forall t \geq t_o
\]

(13)

Also figure 2 explains the definitions of uniform asymptotic stability.

**Instability**: The equilibrium point \( x = 0 \) is said to be unstable if it is not stable:

The following definition of asymptotic stability entails the convergence of system's trajectories towards the equilibrium point:

**Asymptotic Stability**: The equilibrium point \( x = 0 \) is said to be asymptotically stable if, in addition to being stable:

\[
\forall t_o > 0, \exists \delta(t_o) :
\| x(t) \| \rightarrow 0, \text{ as } t \rightarrow \infty
\]

(14)

Therefore in the case of asymptotic stability, systems trajectories initiating sufficiently close to the equilibrium point will eventually converge to it. All definitions have been given with respect to the equilibrium point \( x = 0 \). Equilibria others than the origin can be analogously analysed after a suitable coordinate transformation which translates the origin into the equilibrium point of interest [18].

**B. Stability Criteria**:

Stability analysis of nonlinear systems is largely based on the use of the two stability criteria firstly introduced by A. M. Lyapunov in the late 19th century [21]. The first of them relates the local stability of the equilibrium point of a nonlinear system to the much more easily tractable stability of its linear approximation. The second method of Lyapunov, also known as the Lyapunov's direct method, is based on the use of an energy function.
Since it will be used in subsequent analysis is presented in the various open literatures.

1) Lyapunov's Linearization Method:

It is well known that for the linear system:

\[ x = Ax, A \in \mathbb{R}^{n \times n} \]  
\[ x(0) = x_0 \]  
(15)

The time evolution of state variables, in case \( A \) has distinct eigen values is given by:

\[ x(t) = \sum_{i=1}^{n} \phi_i \psi_i x_0 e^{\lambda_i t} \]  
(16)

where:

- \( \lambda_i \) is the (possibly complex) i-th eigenvalue of the state matrix \( A \).
- \( \phi_i \) is the right eigenvector of the state matrix \( A \) corresponding to the i-th eigenvalue \( \lambda_i \).
- \( \psi_i \) is the left eigenvector of the state matrix \( A \) corresponding to the i-th eigenvalue \( \lambda_i \).

From equation (16) it is easily derived that the origin is:

- **Stable**: if none of the eigen-values has positive real parts;
- **Asymptotically stable**: if all eigen-values have negative real parts;
- **Unstable**: if at least one eigenvalue has positive real part;

The Lyapunov's first method is a straightforward extension of this criterion to general nonlinear systems, based on the fact that, assuming \( f(x) \) continuously differentiable:

\[ \Delta x = \frac{\partial f}{\partial x} \Delta x + f_{h.o.t}(\Delta x), \Delta x = x - x^* \]  
(17)

where \( f_{h.o.t} \) denotes higher order terms. The system:

\[ \Delta x = J \Delta x, J = \left( \frac{\partial f}{\partial x} \right)_{x = x^*} \]  
(18)

is called the linearization of the original nonlinear system. The relationship between the actual nonlinear system and its linearization is summarised in the following:

**Theorem Lyapunov's linearization method:**

- If all eigen-values of \( J \) have negative real parts than the equilibrium point \( x^* \) of the actual nonlinear system is asymptotically stable.
- If at least one eigenvalue of \( J \) has positive real part than the equilibrium point \( x^* \) of the actual nonlinear system is unstable.
- If there exists at least one eigenvalue of \( J \) with zero real part, than, from first order analysis, nothing can be said on stability of the equilibrium point \( x^* \) of the actual nonlinear system.

Differently from the linear case, nonlinear systems with eigen-values on the imaginary \( j\omega \) axis can either be stable, even asymptotically, or unstable. In this case analysis of higher order terms, which affect the so called center manifold, is necessary to draw conclusions about the stability of the equilibrium point [19, 20].

4. DEFINITIONS, CLASSIFICATIONS, AND DYNAMIC PHENOMENA REGARDING WITH POWER SYSTEM STABILITY

In this section, we provide a formal definition of power system stability. The intent is to provide a physically based definition which, while conforming to definitions from system theory, is easily understood and readily applied by power system engineering practitioners.

**A. Proposed Definition of Power System Stability in Power Systems:**

The proposed definitions of power system stability given in open literatures as follows:

"Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact".
B. Classification of Power System Stability in Power System Networks:

Power system stability is essentially a single problem; however, the various forms of instabilities that a power system may undergo cannot be properly understood and effectively dealt with by treating it as such. Because of high dimensionality and complexity of stability problems, it helps to make simplifying assumptions to analyze specific types of problems using an appropriate degree of detail of system representation and appropriate analytical techniques. Analysis of stability, including identifying key factors that contribute to instability and devising methods of improving stable operation, is greatly facilitated by classification of stability into appropriate categories [10]. Classification, therefore, is essential for meaningful practical analysis and resolution of power system stability problems.

The classification of power system stability proposed here is based on the following considerations [10]:

- The physical nature of the resulting mode of instability as indicated by the main system variable in which instability can be observed.
- The size of the disturbance considered which influences the method of calculation and prediction of stability.
- The devices, processes, and the time span that must be taken into consideration in order to assess stability.
- The appropriate method of calculation and prediction of stability.

Fig. 1 gives the overall picture of the power system stability problem, identifying its categories and subcategories. The following are descriptions of the corresponding forms of stability phenomena.

1. Rotor Angle Stability of Power Systems:

Rotor angle stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. It depends on the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system. Instability that may result occurs in the form of increasing angular swings of some generators leading to their loss of synchronism with other generators.

The rotor angle stability problem involves the study of the electromechanical oscillations inherent in power systems. A fundamental factor in this problem is the manner in which the power outputs of synchronous machines vary as their rotor angles change. Under steady-state conditions, there is equilibrium between the input mechanical torque and the output electromagnetic torque of each generator, and the speed remains constant. If the system is perturbed, this equilibrium is upset, resulting in acceleration or deceleration of the rotors of the machines according to the laws of motion of a rotating body. If one generator temporarily runs faster than another, the angular position of its rotor relative to that of the slower machine will advance. The resulting angular difference transfers part of the load from the slow machine to the fast machine, depending on the power-angle relationship. This tends to reduce the speed difference and hence the angular separation. The power-angle relationship is highly nonlinear. Beyond a certain limit, an increase in angular separation is accompanied by a decrease in power transfer such that the angular separation is increased further. Instability results if the system cannot absorb the kinetic energy corresponding to these rotor speed differences. For any given situation, the stability of the system depends on whether or not the deviations in angular positions of the rotors result in sufficient restoring torques [10]. Loss of synchronism can occur between one machine and the rest of the system, or between groups of machines, with synchronism maintained within each group after separating from each other.

The change in electromagnetic torque of a synchronous machine following a perturbation can be resolved into two components:
Damping torque component, in phase with the speed deviation.

- Synchronizing torque component, in phase with rotor angle deviation.
- Damping torque component, in phase with the speed deviation.

System stability depends on the existence of both components of torque for each of the synchronous machines. Lack of sufficient synchronizing torque results in a periodic or non-oscillatory instability, whereas lack of damping torque results in oscillatory instability.

For convenience in analysis and for gaining useful insight into the nature of stability problems, it is useful to characterize rotor angle stability in terms of the following two subcategories:

- Small-disturbance (or small-signal) rotor angle stability: is concerned with the ability of the power system to maintain synchronism under small disturbances. The disturbances are considered to be sufficiently small that linearization of system equations is permissible for purposes of analysis [10].

  - Small-disturbance stability depends on the initial operating state of the system. Instability that may result can be of two forms: i) increase in rotor angle through a non oscillatory or a periodic mode due to lack of synchronizing torque, or ii) rotor oscillations of increasing amplitude due to lack of sufficient damping torque.

  - In today’s power systems, small-disturbance rotor angle stability problem is usually associated with in sufficient damping of oscillations. The periodic instability problem has been largely eliminated by use of continuously acting generator voltage regulators; however, this problem can still occur when generators operate with constant excitation when subjected to the actions of excitation limiters (field current limiters).

  - Small-disturbance rotor angle stability problems maybe either local or global in nature. Local problems involve a small part of the power system, and are usually associated with rotor angle oscillations of a single power plant against the rest of the power system. Such oscillations are called local plant mode oscillations. Stability (damping) of these oscillations depends on the strength of the transmission system as seen by the power plant, generator excitation control systems and plant output [10].

  - Global problems are caused by interactions among large groups of generators and have widespread effects. They involve oscillations of a group of generators in one area swinging against a group of generators in another area. Such oscillations are called inter-area mode oscillations. Their characteristics are very complex and significantly differ from those of local plant mode oscillations. Load characteristics, in particular, have a major effect on the stability of inter-area modes [10].

  - The time frame of interest in small-disturbance stability studies is on the order of 10 to 20 seconds following a disturbance.

- Large-disturbance rotor angle stability or transient stability: as it is commonly referred to, is concerned with the ability of the power system to maintain synchronism when subjected to a severe disturbance, such as a short circulation a transmission line. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship.

  - Transient stability depends on both the initial operating state of the system and the severity of the disturbance. Instability is usually in the form of a periodic angular separation due to insufficient synchronizing torque, manifesting as first swing instability. However, in large power systems, transient instability may not always occur as first swing instability associated with a single mode; it could be a result of superposition of a slow inter-area swing mode and a local-plant swing mode causing a large excursion of rotor angle beyond the first swing [10]. It could also be a result of nonlinear effects affecting a single mode causing instability beyond the first swing.

  - The time frame of interest in transient stability studies is usually 3 to 5 seconds following the disturbance. It may extend to 10–20 seconds for very large systems with dominant inter-area swings.

As identified in Fig. 1, small-disturbance rotor angle stability as well as transient stability are categorized as short term phenomena.
The term *dynamic stability* also appears in the literature as a class of rotor angle stability. However, it has been used to denote different phenomena by different authors. In the North American literature, it has been used mostly to denote small-disturbance stability in the presence of automatic controls (particularly, the generation excitation controls) as distinct from the classical “steady-state stability” with no generator controls [10].

Dynamic phenomena related to rotor angle stability, which is the main subject of the present thesis, are typically confined in a time frame ranging from tenth of to few tens of seconds. Torsional transients in generators turbine shafts, which are associated with time constants in the sub synchronous range, i.e. tens of millisecond, could also give rise to instability phenomena which should be taken into account in several practical situations.

A properly working power system is operated in such a way as to constantly maintain a balance between the powers produced in generators and that absorbed by the loads. In current power systems electric power is being produced, almost totally, in conventional power plants where either a thermal or an hydraulic source of energy is transformed into electric energy by means of synchronous generators. Although this situation might change in future due to the constant increase in the amount of distributed generation which is based on the use of alternative energy sources, i.e. wind, sun, fuel cells and so on, which are coupled to the transmission network through power electronics based converters, the synchronous generator will remain the main tool for energy conversion for a longtime to come.

The ability of all synchronous machines, interconnected through the transmission network, to maintain a synchronous operation is referred to as *rotor angle stability*. Steady state operation is therefore characterised, for each synchronous generator, by a state of equilibrium between the mechanical torque applied by the prime mover through the turbine shaft and the electric torque due to the loading of the generator. If an unbalance arises as a consequence of a disturbance, the state of equilibrium is perturbed and some generators rotors may accelerate while others may decelerate. The behavior of the system after the perturbation largely depends upon the amplitude of the disturbance. Actual systems must operate in an equilibrium in which they should be able to withstand at least small disturbances. This is possible due to the nature of power-angle relationship for a synchronous generator, which states that the electric power and hence electric torque increases sinusoidally as the angle with respect to the rest of the system increases. Due to the nonlinear nature of the power-angle relationship, a large perturbation and hence a large displacement of a machine angle against the rest of the system, will eventually result in a decrease in the electrical power injected into the network which will lead to a further unbalance between mechanical torque and electrical torque and thus produce an increase in angular separation. A classical classification of rotor angle related stability analysis is roughly based on the magnitude of the disturbance.

2. **Voltage Stability of power Systems:**

*Voltage stability* refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. Instability that may result occurs in the form of a progressive fall or rise of voltages of some buses. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and other elements by their protective systems leading to cascading outages. Loss of synchronism of some generators may result from these outages or from operating conditions that violate field current limit [22]-[23].

Progressive drop in bus voltages can also be associated with rotor angle instability. For example, the loss of synchronism of machines as rotor angles between two groups of machines approach 180 causes rapid drop in voltages at intermediate points in the network close to the electrical center [10]. Normally, protective systems operate to separate the two groups of machines and the voltages recover to levels depending on the post-separation conditions. If, however, the system is not so separated, the voltages near the electrical center rapidly oscillate between high and low values as a result of repeated “pole slips” between the two groups of machines. In contrast, the type of sustained fall of voltage that is related to voltage instability involves loads and may occur where rotor angle stability is not an issue.
The term *voltage collapse* is also often used. It is the process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system [10], [16]. Stable (steady) operation at low voltage may continue after transformer tap changers reach their boost limit, with intentional and/or unintentional tripping of some load. Remaining load tends to be voltage sensitive, and the connected demand at normal voltage is not met.

The driving force for voltage instability is usually the loads; in response to a disturbance, power consumed by the loads tends to be restored by the action of motor slip adjustment, distribution voltage regulators, tapping transformers, and thermostats. Restored loads increase the stress on the high voltage network by increasing the reactive power consumption and causing further voltage reduction. A run-down situation causing voltage instability occurs when load dynamics attempt to restore power consumption beyond the capability of the transmission network and the connected generation [10], [23]–[24].

A major factor contributing to voltage instability is the voltage drop that occurs when active and reactive power flow through inductive reactances of the transmission network; this limits the capability of the transmission network for power transfer and voltage support. The power transfer and voltage support are further limited when some of the generators hit their field or armature current time-overload capability limits. Voltage stability is threatened when a disturbance increases the reactive power demand beyond the sustainable capacity of the available reactive power resources.

While the most common form of voltage instability is the progressive drop of bus voltages, the risk of overvoltage instability also exists and has been experienced at least on one system [25]. It is caused by a capacitive behavior of the network (EHV transmission lines operating below surge impedance loading) as well as by under excitation limiters preventing generators and/or synchronous compensators from absorbing the excess reactive power. In this case, the instability is associated with the inability of the combined generation and transmission system to operate below some load level. In their attempt to restore this load power, transformer tap changers cause long-term voltage instability.

Voltage stability problems may also be experienced at the terminals of HVDC links used for either long distance or back-to-back applications [26], [27]. They are usually associated with HVDC links connected to weak ac systems and may occur at rectifier or inverter stations, and are associated with the unfavorable reactive power “load” characteristics of the converters. The HVDC link control strategies have a very significant influence on such problems, since the active and reactive power at the ac/dc junction are determined by the controls. If the resulting loading on the ac transmission stresses it beyond its capability, voltage instability occurs. Such a phenomenon is relatively fast with the time frame of interest being in the order of one second or less. Voltage instability may also be associated with converter transformer tap-changer controls, which is a considerably slower phenomenon [27].

Recent developments in HVDC technology (voltage source converters and capacitor commutated converters) have significantly increased the limits for stable operation of HVDC links in weak systems as compared with the limits for line commutated converters.

One form of voltage stability problem that results in uncontrolled over voltages is the self-excitation of synchronous machines. This can arise if the capacitive load of a synchronous machine is too large. Examples of excessive capacitive loads that can initiate self-excitation are open ended high voltage lines and shunt capacitors and filter banks from HVDC stations [28]. The over voltages that result when generator load changes to capacitive are characterized by an instantaneous rise at the instant of change followed by a more gradual rise. This latter rise depends on the relation between the capacitive load component and machine reactances together with the excitation system of the synchronous machine. Negative field current capability of the exciter is a feature that has a positive influence on the limits for self-excitation.

As in the case of rotor angle stability, it is useful to classify voltage stability into the following subcategories:

Voltage instability in the power system occurs due to incapability of power system to supply loads under disturbances. Disturbances may be either large or small in nature. Accordingly, voltage stability can be classified in following two subcategories:
Large-disturbance voltage stability: refers to the system’s ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. This ability is determined by the system and load characteristics, and the interactions of both continuous and discrete controls and protections. Determination of large-disturbance voltage stability requires the examination of the nonlinear response of the power system over a period of time sufficient to capture the performance and interactions of such devices as motors, under load transformer tap changers, and generator field-current limiters. The study period of interest may extend from a few seconds to tens of minutes.

Small-disturbance voltage stability: refers to the system’s ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load. This form of stability is influenced by the characteristics of loads, continuous controls, and discrete controls at a given instant of time. This concept is useful in determining, at any instant, how the system voltages will respond to small system changes. With appropriate assumptions, system equations can be linearized for analysis thereby allowing computation of valuable sensitivity information useful in identifying factors influencing stability. This linearization, however, cannot account for nonlinear effects such as tap changer controls (dead bands, discrete tap steps, and time delays). Therefore, a combination of linear and nonlinear analyzes is used in a complementary manner [29].

As noted above, the time frame of interest for voltage stability problems may vary from a few seconds to tens of minutes. Therefore, voltage stability may be either a short-term or a long-term phenomenon as identified in Figure 1.

Short-term voltage stability: involves dynamics of fast acting load components such as induction motors, electronically controlled loads, and HVDC converters. The study period of interest is in the order of several seconds, and analysis requires solution of appropriate system differential equations; this is similar to analysis of rotor angle stability. Dynamic modeling of loads is often essential.

In contrast to angle stability, short circuits near loads are important. It is recommended that the term transient voltage stability not be used.

Long-term voltage stability: involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters. The study period of interest may extend to several or many minutes, and long-term simulations are required for analysis of system dynamic performance [30], [31]. Stability is usually determined by the resulting outage of equipment, rather than the severity of the initial disturbance. Instability is due to the loss of long-term equilibrium (e.g., when loads try to restore their power beyond the capability of the transmission network and connected generation), post-disturbance steady-state operating point being small-disturbance unstable, or a lack of attraction toward the stable post-disturbance equilibrium (e.g., when a remedial action is applied too late) [23]. The disturbance could also be a sustained load buildup (e.g., morning load increase). In many cases, static analysis [30] can be used to estimate stability margins, identify factors influencing stability, and screen a wide range of system conditions and a large number of scenarios. Where timing of control actions is important, this should be complemented by quasi-steady-state time-domain simulations [23].

3. Frequency Stability of Power Systems:

Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. It depends on the ability to maintain/restore equilibrium between system generation and load, with minimum unintentional loss of load. Instability that may result occurs in the form of sustained frequency swings leading to tripping of generating units and/or loads.

Severe system upsets generally result in large excursions of frequency, power flows, voltage, and other system variables, thereby invoking the actions of processes, controls, and protections that are not modeled in conventional transient stability or voltage stability studies. These processes may be very slow, such as boiler dynamics, or only
Corresponding to the response of devices such as controls and protections, to several minutes, under frequency load shedding and generator activated will range from fraction of seconds, times of the processes and devices that are frequency excursions, the characteristic phenomena or a phenomenon. An example of short-term frequency instability is the formation of an under generated island with insufficient under frequency load shedding such that frequency decays rapidly causing blackout of the island within a few seconds. On the other hand, more complex situations in which frequency instability is caused by steam turbine over speed controls or boiler/reactor protection and controls are longer-term phenomena with the time frame of interest ranging from tens of seconds to several minutes.

During frequency excursions, the characteristic times of the processes and devices that are activated will range from fraction of seconds, corresponding to the response of devices such a sunder frequency load shedding and generator controls and protections, to several minutes, corresponding to the response of devices such as prime mover energy supply systems and load voltage regulators. Therefore, as identified in Fig. 1, frequency stability may be a short-term phenomenon or a long-term phenomenon. An example of short-term frequency instability is the formation of an under generated island with insufficient under frequency load shedding such that frequency decays rapidly causing blackout of the island within a few seconds. On the other hand, more complex situations in which frequency instability is caused by steam turbine over speed controls or boiler/reactor protection and controls are longer-term phenomena with the time frame of interest ranging from tens of seconds to several minutes [32].

We have classified power system stability for convenience in identifying causes of instability, applying suitable analysis tools, and developing corrective measures. In any given situation, however, any one form of instability may not occur in its pure form. This is particularly true in highly stressed systems and for cascading events; as systems fail one form of instability may ultimately lead to another form. However, distinguishing between different forms is important for understanding the underlying causes of the problem in order to develop appropriate design and operating procedures. While classification of power system stability is an effective and convenient means to deal with the complexities of the problem, the overall stability of the system should always be kept in mind. Solutions to stability problems of one category should not be at the expense of another. It is essential to look at all aspects of the stability phenomenon and at each aspect from more than one viewpoint.

4. Transient Stability of Power Systems:

Among the large disturbances which could affect the transient stability of the system, short circuits and possibly subsequent tripping of the faulted transmission line are the most common. Instability which may a rises from these severe disturbances is often characterized by a constantly increasing angular separation without any periodicity. This kind of behavior is often referred to as first swing instability. As it is the case in small signal stability non oscillatory unstable behavior was largely eliminated by the widespread use of fast acting regulators. Most common instability behavior is therefore in the form of large oscillations with increasing amplitude among generators of different areas.

In actual power system the classification based on the nature of the disturbance could result quite artificial. Some real occurrences of system instability, although caused by large disturbances, i.e. generator tripping, manifested as small signal stability problem, i.e. oscillations of growing amplitude.

5. Dynamic Stability of Power Systems:

One of the most important parts of power system stability is dynamic stability. Controlling devices to improve dynamic stability of power systems are
called power systems stabilizers (PSS) and FACTS controllers. The problem is to determine the proper place of stabilizers next to generators which needs those stabilizers. Changes and expansions of the network may cause movement of stabilizers. One solution of this problem is collecting the stabilizers in one place of network and connecting them to network through a channel. In the open literatures, we use internet as a vast and easy-accessible network instead of connecting channel which we try to settle the limitations by using two new methods.

6. **Damping of Power System Oscillation:**

As described in previous sections, an oscillation of synchronous generator rotor with respect to network reference is usually in the range of 0.2-2Hz. This is, however, a result of the simplifying assumptions used in generator's rotor representation, which is considered to be constituted by a single rigid mass. The rotor of an actual generating unit is a very complex mechanical system obtained by the interconnection of several shaft sections. This structure has therefore several torsional modes of vibration, with each section oscillating against the others [10]. Such oscillations can appear at both sub-synchronous. And super synchronous frequencies, ranging from few tens to few hundreds of Hz. Potentially dangerous undamped sub-synchronous oscillations appear as a result of the interaction of torsional modes with synchronous generators' controllers or series capacitor compensated transmission lines. In the latter case, adverse interactions result in the so-called sub-synchronous resonance (SSR) phenomena [34]-[35].

6. **Dynamical phenomena in power systems:**

Due to the large amount of different devices contemporaneously acting in electric power systems, they are affected by several complex dynamical phenomena. In order to better understand the causes of each phenomenon and make the system working properly, it is of great importance to analyze the range of dynamics which have a role in system's behavior. A classification of dynamical phenomena could therefore result very useful for analysis purposes. The need for classification arises from the necessity to divide such a complex problem as system stability into sub-problems, utilizing simplifying assumptions with the aim of rendering each sub-problem more amenable to mathematical and/or numerical analysis. Simplifications, on the other hand, should be carefully made in order to maintain a sufficient degree of approximation in system's response.

Figure 3 show that a schematic drawing which illustrates a commonly used time-scale decomposition of dynamical phenomena in power systems [36]-[37].

A first rough classification can be made separating slow from fast phenomena, since very fast transients such as those due to lightning or switching of circuit breakers die out very quickly, i.e. in the order of $10^{-4}$ s compared to slow phenomena such as load restoration or secondary/tertiary regulation involved in voltage or frequency stability evaluation which require study periods spanning several minutes or even hours. A word of caution is necessary, because although classifications may result very useful, many phenomena are so intertwined that in some situations it is difficult to attribute the cause of a particular failure to a single phenomenon.

5. **CONCEPTS AND RELATIONSHIP BETWEEN RELIABILITY, SECURITY, AND POWER SYSTEM STABILITY IN POWER SYSTEM NETWORKS**

In this section, we discuss the relationship between the concepts of power system reliability, security, and stability. We will also briefly describe how these terms have been defined and used in practice.

A. **Conceptual Relationship** [38], [39]
Reliability of a power system: refers to the probability of its satisfactory operation over the long run. It denotes the ability to supply adequate electric service on a nearly continuous basis, with few interruptions over an extended time period.

Security of a power system: refers to the degree of risk in its ability to survive imminent disturbances (contingencies) without interruption of customer service. It relates to robustness of the system to imminent disturbances and, hence, depends on the system operating condition as well as the contingent probability of disturbances.

Stability of a power system: as discussed in Section II, refers to the continuance of intact operation following a disturbance. It depends on the operating condition and the nature of the physical disturbance.

The following are the essential differences among the three aspects of power system performance:

- Reliability is the overall objective in power system design and operation. To be reliable, the power system must be secure most of the time. To be secure, the system must be stable but must also be secure against other contingencies that would not be classified as stability problems e.g., damage to equipment such as an explosive failure of a cable, fall of transmission towers due to ice loading or sabotage. As well, a system may be stable following a contingency, yet insecure due to post-fault system conditions resulting in equipment overloads or voltage violations.

- System security may be further distinguished from stability in terms of the resulting consequences. For example, two systems may both be stable with equal stability margins, but one may be relatively more secure because the consequences of instability are less severe.

- Security and stability are time-varying attributes which can be judged by studying the performance of the power system under a particular set of conditions. Reliability, on the other hand, is a function of the time-average performance of the power system; it can only be judged by consideration of the system’s behavior over an appreciable period of time.

C. NERC Definition of Reliability [40]

NERC (North American Electric Reliability Council) defines power system reliability as follows.

“Reliability, in a bulk power electric system, is the degree to which the performance of the elements of that system results in power being delivered to consumers within accepted standards and in the amount desired. The degree of reliability may be measured by the frequency, duration, and magnitude of adverse effects on consumer service”.

Reliability can be addressed by considering two basic functional aspects of the power systems:

- Adequacy—he ability of the power system to supply the aggregate electric power and energy requirements of the customer at all times, taking into account scheduled and unscheduled outages of system components.

- Security—the ability of the power system to withstand sudden disturbances such as electric short circuits or non anticipated loss of system components.

The above definitions also appear in several IEEE and CIGRE Working Group/Task Force documents [41], [42].

Other alternative forms of definition of power system security have been proposed in the literature. For example, in reference [43], security is defined in terms of satisfying a set of inequality constraints over a subset of the possible disturbances called the “next contingency set.”

6. SHORTCOMING OF LITERATURE SURVEY

One of the major causes of voltage instability is the reactive power limits of the power systems. The many literatures have proposed solutions for this problem, by using suitable location of Flexible AC Transmission Systems (FACTS) and proper coordination between FACTS controllers to improve voltage stability of the power systems. Hence, improving the systems reactive power handling capacity via Flexible AC transmission System (FACTS) device is a remedy for prevention of voltage instability and hence voltage collapse.

The several literatures are proposed the different methods/techniques for enhancement of power system stability by placement of FACTS controllers, and coordination of FACTS
controllers, one of the shortcomings of such methods is that they only consider the normal state of system. However, voltage collapses are mostly initiated by a disturbance (e.g. the outage of a line, or fault on system or generation unit, or increased in load demand). So to locate FACTS devices, consideration of contingency conditions is more important than consideration of normal state of system and some approaches are proposed to locate of FACTS devices with consideration of contingencies, too presented in the many literatures.

7. IMPROVEMENT OF POWER SYSTEM STABILITY BY PLACEMENT AND COORDINATION OF FACTS CONTROLLERS IN AN INTEGRATED POWER SYSTEM NETWORKS

A. By Placement of FACTS Controllers in an integrated power system networks

1. Small Signal Voltage Stability of an integrated power system networks:

While small signal and transient instability phenomena are mostly related to synchronous generators and their control, voltage stability is mostly related to network and loads. Voltage stability can be defined as the ability of a power system to maintain voltage magnitude at all buses within acceptable limits after the system has experienced a disturbance. The loss of equilibrium between load demand and load supply is the main cause of voltage instability, which results in unacceptable low voltages across the network [44]. Voltage instability phenomena often appear as a sudden decrease of voltage therefore called voltage collapse. Many loads supplied by a power system are controlled in such a way as to have some sort of restorative behavior. Large industrial motors drives, thermostatically controlled heating loads, tap-changing transformers are examples of loads that respond to disturbances trying to restore their power consumption. This restorative action has the effect to further increase the stress on an already stressed system. In particular reactive power demand could increase beyond the available capability, leading to the intervention of limiting protections such as over excitation limiters in synchronous generators.

A new method called the Extended Voltage Phasors Approach (EVPA) has been suggested for placement of FACTS controllers in power systems for identifying the most critical segments/bus in power system from the voltage stability view point in [45]. A residues based approach has been proposed for allocation of FACTS controllers in power system to enhance the system stability [46]-[47]. A sensitivity based approach has been proposed for placement of FACTS controllers in open power markets to reduce the flows in heavily loaded lines, resulting in an increased loadability, low system loss, improved voltage stability of the network, reduced cost of production and fulfilled contractual requirement by controlling the power flows in the network in [48]-[49]. A sensitivity based approach called Bus Static Participation Factor (BSPF) has been proposed for determine the optimal location of static VAR compensator (SVC) for voltage security enhancement in [50]. In [51], a sensitivity analysis method has been proposed for determine the optimal placement of static VAR compensator (SVC) for voltage security enhancement in Algerian Distribution System. Reference [52], presents a sensitivity based approach has been proposed for optimal placement of UPFC to enhance voltage stability margin under contingencies. In [53], a sensitivity based technique used for determine the minimum amount of shunt reactive power (VAr) support which indirectly maximizes the real power transfer before voltage collapse is encountered. Sensitivity information that identifies weak buses is also available for locating effective VAR injection sites. A new approach based on sensitivity indices has been used for the optimal placement of various types of FACTS controllers such as TCSC, TCPAR and SVC in order to minimize total system reactive power loss and hence maximizing the static voltage stability in [54]. A mixed integer optimization programming algorithm has been proposed for allocation of FACTS controllers in power system for security enhancement against voltage collapse and corrective controls, where the control effects by the devices to be installed are evaluated together with the other controls such as load shedding in contingencies to compute an optimal VAR planning [55]. In [56], a mixed integer non-linear optimization programming algorithm is used for determine the type, optimal number, optimal location of the TCSC for loadability and voltage stability enhancement in deregulated electricity markets. Chang and Huang et al. showed that a hybrid optimization programming algorithm for optimal placement of SVC for voltage stability reinforcement [57]. Orfanianni and Bacher et al. suggested an optimization-based methodology is used for
identify key locations of TCSC and UPFC include the nonlinear constraints of voltage limitation, zero megawatt active power exchange, voltage control, and reactive power exchange in the ac networks [58]. A stochastic searching algorithm called as genetic algorithm has been proposed for optimal placement of static VAR compensation for enhancing voltage stability in [59]. Reference [60], genetic algorithm (GA) and particle swarm optimization (PSO) has been proposed for optimal location and parameter setting of UPFC for enhancing power system security under single contingencies. References [61], [62], a novel optimization based methodology such as a simulated annealing has been proposed for optimal location of FACTS devices such as TCSC and SVC in order to relieve congestion in the transmission line while increasing static security margin and voltage profile of power system networks. In [63], the Goal Attainment (GA) method based on the SA approach is applied to solving general multi-objective VAR planning problems by assuming that the Decision Maker (DM) has goals for each of the objective functions. The VAR planning problem involves the determination of location and sizes of new compensators considering contingencies and voltage collapse problems in a power system. Rashed et al. suggested a Genetic Algorithm (GA) and PSO techniques for optimal location and parameter setting of TCSC to improve the power transfer capability, reduce active power losses, improve stabilities of the power network, and decrease the cost of power production and to fulfill the other control requirements by controlling the power flow in multi-machine power system network [64].

A Graph Search Algorithm has been addressed for optimal placement of fixed and switched capacitors on radial distribution systems to reduce power and energy losses, increases the available capacity of the feeders, and improves the feeder voltage profile [65]. In [66], the theory of the normal forms of diffeomorphism algorithm has been addressed for the SVC allocation in multi-machine power system for power system voltage stability enhancement. In [67], a knowledge and algorithm based approach is used to VAR planning in a transmission system. The VAR planning problem involves the determination of location and sizes of new compensators considering contingencies and voltage collapse problems in a power system. Fang and Ngan et al. [68] suggested an augmented Lagrange Multipliers approach for optimal location of UPFC in power systems to enhance the steady state performance and significantly increase the loadability of the system.

Reference [69] discusses the effect of TCSC on the small signal voltage stability for a simple power system with an infinitive bus and a dynamic load. The small signal voltage stability region is derived for this simple system. The paper has one serious drawback that infinitive bus is not a good model for a generator for voltage stability studies since only the voltage instability caused by insufficient transfer capability can be examined. It is well known that the generator field current limiting action limits the output of the reactive power, which is essential in the voltage stability analysis. Canizares and Faur studied the effects of SVC and TCSC on voltage collapse [70]. In [71], voltage stability assessment of the system with shunt compensation devices including shunt capacitors, SVC and STATCOM is studied and compared in the IEEE 14-bus test system. In [72], Effects of STATCOM, SSSC and UPFC on Voltage Stability is studied. Study of STATCOM and UPFC Controllers for Voltage Stability Evaluated by Saddle-Node Bifurcation Analysis is carry out in [73]. Also In [74], Static Voltage Stability Margin Enhancement Using STATCOM, TCSC and SSSC is compared. So far no work has been reported in open literature for the effects of SVC, STATCOM, TCSC and UPFC on voltage stability. Reference [75], considers four FACTS controllers in order to increase the loadability margin of a power system. The appropriate representation including the equations in the DC parts of these FACTS devices is incorporated in the continuation power flow (CPF) process in static voltage stability study. Based on the above observation, an effort made in this paper is to compare the merits and demerits of some FACTS devices, namely, SVC, STATCOM, TCSC and UPFC, in terms of Maximum Loading Point (MLP) in static voltage stability study. This leads to a more practical solution in terms of MLP or voltage stability margin, which may be useful for utilities to select the most beneficial FACTS devices among SVC, STATCOM, TCSC and UPFC.

Kumkratug and Haque [76] demonstrated the capability of the SSSC to control the line flow and to improve the system stability. A control strategy of an SSSC to enlarge the stability region has been derive during the direct method. The effectiveness of the SSSC to extend the critical clearing time has been confirmed through simulation results on a single machine infinite bus system. The effectiveness of the STATCOM to
control the power system voltage was presented in [77]. However, the effectiveness of the STATCOM to enhance the angle stability has not been addressed. Hammad [78] presented a fundamental analysis of the application of SVC for enhancing the power systems stability. Messina and Barocio [79] studied the nonlinear modal interaction in stressed power systems with multiple SVC voltage support. It was observed that SVC controls can significantly influence nonlinear system behavior especially under high-stress operating conditions and increased SVC gains. Rosso et al. [80] presented a detailed analysis of TCSC control performance for improving power system stability with different input signals. Namely, the line active power and the line current magnitude were considered. The simulation results demonstrated that the TCSC damping capability is more effective with line current input signal.

Interline Power Flow Controller (IPFC) is an extension of the UPFC, which can be efficiently used to control the transmission line parameters in case of interconnected systems [81]. Enhanced power flow and hence better stability is ensured by real power exchange between under utilized and over loaded transmission lines and by providing the necessary reactive power support.

In [82], paper presented an application of Single-input Fuzzy Logic Controller (SFLC) to determine the control signal of a Static Compensator (STATCOM) synchronous for improvement of power system stability. This compensation scheme is relevant to Flexible AC Transmission systems (FACTS) technology which is used worldwide to improve system dynamic performance. STATCOM improves the damping of electromechanical oscillations when used in transmission systems. The SFLC uses only one input variable which is called assigned distance. The SFLC has the advantages of reduced number of rules. Thus, generation, estimation and tuning of control rules are much easier while comparing with the existing conventional Fuzzy Logic Controllers (FLCs). The proposed control method is applied to control the AC and DC bus voltage of a STATCOM connected at a load bus in a Single Machine Infinite Bus (SMIB) System and also to improve the power system stability.

2. Transient Stability of an integrated power system networks:

A structure preserving energy margin sensitivity based analysis has been addressed for determine the effectiveness of FACTS devices to improve transient stability of a power system in [83]. Reference [84], suggested a Trajectory Sensitivity Analysis (TSA) technique for the evaluation of the effect of TCSC placement on transient stability.

3. Rotor Angle Stability of an integrated power system networks:

Reference [85], presented a simple method of evaluating the first swing stability of a large power system in the presence of various flexible ac transmission system (FACTS) devices. First a unified power flow controller (UPFC) and the associated transmission line are considered and represented by an equivalent pie-circuit model. The above model is then carefully interfaced to the power network to obtain the system reduced admittance matrix which is needed to generate the machine swing curves. The above pie circuit model can also be used to represent other FACTS devices (SSSC and STATCOM) by selecting appropriate values of control parameters of the UPFC. The complex voltage at two end buses of the pie-circuit model is also evaluated during simulation to implement various existing control strategies of FACTS devices and to update the reduced admittance matrix. The effectiveness of the proposed method of generating dynamic response and hence evaluating first swing stability of a power system in the presence of various FACTS devices is tested on the ten-machine New England system and the 20-machine IEEE test system in this literature.

Chaudhuri et al. [86],[87], demonstrated that the use of global stabilizing signals for effective damping of multiple swing modes through single FACTS device is one of the potential options worth exploring.

Farsangi et al. [88] presented the minimum singular value, the right half plane zeros, the relative gain array, and the Hankel singular values as indicators to find the stabilizing signals of FACTS devices for damping inter-area oscillations. Kulkarni and Padiyar [89] proposed a location index based on circuit analogy for the series FACTS controllers. The feedback signals used were synthesized using local measurements. The method is validated on two different multi machine power systems and very important comments have been highlighted in this work.

Power system stability enhancement [90] via excitation and FACTS-based stabilizers is thoroughly investigated in this paper. This study presents a singular value decomposition-based
approach to assess and measure the controllability of the poorly damped electromechanical modes by different control inputs. The design problem of a power system stabilizer and different FACTS-based stabilizers is formulated as an optimization problem. An eigenvalue-based objective function is introduced to increase the system damping and improve the system response. Then, a real-coded genetic algorithm is employed to search for optimal controller parameters. In addition, the damping characteristics of the proposed schemes are evaluated in terms of the damping torque coefficient with different loading conditions. The proposed stabilizers are tested on a weakly connected power system with different loading conditions. The damping torque coefficient analysis, nonlinear simulation results, and eigenvalue analysis show the effectiveness and robustness of the proposed control schemes over a wide range of loading conditions.

In [91], paper presented a new approach to the implementation of the effect of FACTS devices on damping local modes and inter-area modes of oscillations based on a simple fuzzy logic proportional plus conventional integral controller in a multi-machine power system. The proposed controller uses a combination of a FLC and a PI controller. In comparison with the existing fuzzy controllers, the proposed fuzzy controller combines the advantages of a FLC and a conventional PI controller. By applying this controller to the FACTS devices such as UPFC, TCSC and SVC the damping of local modes and inter-area modes of oscillations in a multi-machine power system will be handled properly. In addition, the paper considers the conventional PI controller and compares its performance with respect to the proposed fuzzy controller. Also the effects of the auxiliary signals in damping multimodal oscillation have been shown. Finally, several fault and load disturbance simulation results are presented to highlight the effectiveness of the proposed FACTS controller in a multi-machine power system.

M. Noroozian [92]-[94], examined the enhancement of multi machine power system stability by use TCSCs and SVCs. SVC was found to be more effective for controlling power swings at higher levels of power transfer; when it design to damp the inter-area modes, it might excite the local modes, and its damping effect dependent on load characteristics. While TCSC is not sensitive to the load characteristic and when it is designed to damp the inter-area modes, it does not excite the local modes.

4. Dynamic Stability of an integrated power system networks:

The emergence of FACTS devices and in particular GTO thyristor-based STATCOM has enabled such technology to be proposed as serious competitive alternatives to conventional SVC [95]. From the power system dynamic stability viewpoint, the STATCOM provides better damping characteristics than the SVC as it is able to transiently exchange active power with the system. Reference [96], presented the modeling of Voltage Sourced Inverter (VSI) type Flexible AC Transmission System (FACTS) controllers and control methods for power system dynamic stability studies. The considered FACTS controllers are the Static Compensator (STATCOM), the Static Synchronous Series Compensator (SSSC), and the Unified Power Flow Controller (UPFC). In this paper, these FACTS controllers are derived in the current injection model, and it is applied to the linear and nonlinear analysis algorithm for power system dynamics studies. The parameters of the FACTS controllers are set to damp the inter-area oscillations, and the supplementary damping controllers and its control schemes are proposed to increase damping abilities of the FACTS controllers. For these works, the linear analysis for each FACTS controller with or without damping controller is executed, and the dynamic characteristics of each FACTS controller are analyzed.

B. By Coordination of FACTS Controllers in an integrated power System networks

1. Small Signal Voltage Stability of an integrated power system networks:

A new methodology has been addressed for the solution of voltage stability when a contingency has occurred, using coordinated control of FACTS devices located in different areas of a power system. An analysis of the initial conditions to determine the voltage stability margins and a contingency analysis to determine the critical nodes and the voltage variations are conducted. The response is carried out by the coordination of multiple type FACTS controllers, which compensate the reactive power, improving the voltage stability margin of the critical modes [97]. Canizares and Faur et al. presented the steady-state models with controls of two FACTS controllers, namely SVC and TCSC, to study their effect on
voltage collapse phenomena in power system to increase system loadability [98]. A new method has been suggested for the potential application of coordinated secondary voltage control by multiple FACTS voltage controllers in eliminating voltage violations in power system contingencies in order to achieve more efficient voltage regulation in a power system. The coordinated secondary voltage control is assigned to the SVCs and Static Compensators (STATCOM) in order to eliminate voltage violations in power system contingencies [99]. A new methodology has been proposed for decentralized optimal power flow control for overlapping area in power systems for the enhancement of the system security [100].

In [101], a new method based on the optimization method is called non-linear optimization programming technique has been addressed for tuning the parameters of the PSS for enhancing small-signal stability. Feng et al. suggested a comprehensive approach for determination of preventive and corrective control strategies to contain voltage collapse in stressed power systems [102]. An immune-based algorithm has been addressed for optimal coordination of local physically based controllers in order to presence or retain mid and long term voltage stability [103]. In [104], a new methodology has been proposed for coordinated control of FACTS devices in power system for security enhancement.

In [105], a genetic algorithm based on the method of inequalities has been addressed for the coordinated synthesis PSS parameters in a multi-machine power system in order to enhance overall system small signal stability. Etingov et al. suggested an emergency control system based on the ANN technique for finding a coordinated control system action (load shedding, generation tripping) to prevent the violation of power system stability [106]. A fuzzy logic based method is used for decentralized coordination of FACTS devices for power system stability enhancement in [107].

Hiyama et al. [108] presented a coordinated fuzzy logic-based scheme for PSS and switched series capacitor modules to enhance overall power system voltage stability. Ramirez et al. [109] presented a technique to design and coordinate PSSs and STATCOM-based stabilizers to enhance the system stability and avoid the adverse interaction among stabilizers. Ramirez et al. [110] extended the work to coordinate among three different types of stabilizers, namely, PSSs, TCSC, and UPFC. The results exhibit a meritorious performance of the coordinated stabilizers. A systematic approach to establish the dynamic model of a multi-machine power system installed with multiple SVCs, TCSCs, TCPSs, STATCOMs, and UPFCs was presented [111]. The adverse interactions among these stabilizers, which may lead to the loss of the system stability, has been examined.

2. Transient Stability of an integrated power system networks:

Tan and Wang et al. showed that an adaptive non-linear coordinated design technique for coordinated design of series and shunt FACTS controllers such as a Static Phase Shifter (SPS) and a Static VAR Compensators (SVC) controller in power systems environments for enhance the transient stability of the power system [112]. A non-linear technique has been proposed for robust non-linear coordinated excitation and SVC control for power systems for enhance the transient stability of the power systems [113]. In [114], an optimization based approach has been suggested for power system optimization and coordination of FACTS controllers to significant transient stability improvement and effective power oscillation damping. Reference [115], a Particle Swarm Optimization (PSO) Algorithm has been suggested for coordinated design of a TCSC controller and PSS in power systems for enhancing the power system stability.

3. Rotor Angle Stability of an integrated power system networks:

Wang et al. [116] have discussed the issue of selection of typical operating conditions for robust design of multiple stabilizers in coordinated manner to damp multimode oscillations in multi machine power systems.

In [117], a co-ordinated control scheme for STATCOM and generator excitation to achieve transient stability, damping and voltage regulation enhancement of power systems is presented. First, the nonlinear model of STATCOM installed in a power system is derived. Then, using the feedback linearisation technique, the nonlinearities of the generator and the STATCOM model are alleviated. With the help of robust control theory, the variation of system structure, the parameter uncertainties and the interconnection between the generator and STATCOM are taken into consideration in the controller design. Only local measurements are required. The performance of the proposed control scheme is evaluated through a real time test by means of the real time digital simulator (RTDS). The results present comparisons of the system...
addressed for the problem of the most effective schemes.

In [118], an eigen value analysis approach has been addressed for the problem of the most effective selection of generating units to be equipped with excitation system stabilizers in multi-machine power systems which exhibit dynamic instability and poor damping of several inter machine modes of oscillations. An eigen value sensitivity based analysis approach has been addressed for design and coordinate multiple stabilizers in order to enhance the electro-mechanical transient behaviour of power systems [119]. In [120], a modal analysis technique has been addressed for coordinated control of inter-area oscillation in the china southern power grid for parameter setting of selected power system stabilizers (PSS) and HVDC damping controllers. In [121], a Decentralized Modal Control (DMC) algorithm has been addressed for simultaneously selecting the power system stabilizers (PSS) parameters in multi-machine power system in order to enhance damping of the power system oscillations. Torsional oscillations are excited as a result of interactions between the shaft systems of steam turbine-generator (T-G) sets and: (1) series capacitor compensated networks, and (2) power system controllers, e.g., excitation systems, governors and HVDC converter controllers. Torsional oscillations impose torsional torques on the shaft sections of T-G sets and as a result of the fatigue phenomenon reduce the life-time of the shaft sections. This problem solved in [122], an eigen value sensitivity based analysis approach has been addressed for coordinated control of SVC and PSSs in power system in order to enhance damping of the power system oscillations. In [123], a modal analysis based technique has been presented for design of robust controllers for damping inter-area oscillations application to the European power system. Gasca and Chow et al. has suggested a modal analysis based technique for the design of damping controllers in multi-machine power system or inter-area oscillations [124]. Ammari et al. [125] has addressed sensitivity and residues based techniques for robust solution for the interaction phenomena between dynamic loads and FACTS controllers for enhance damping of power system oscillations. In [126], a sensitivity based techniques such as a linear matrix inequalities technique has been proposed for the design of robust PSS which places the system poles in acceptable region in the complex plane for a given set of operating and system conditions to enhance the damping of power system oscillations over the entire set of operating conditions. A frequency response technique has been used for coordinated design of under-excitation limiters and power system stabilizers (PSS) in power system for enhance the electro-mechanical damping of power system oscillations [127]. A root locus technique has been proposed for design of power system stabilizers (PSS) for damping out tie-line power oscillations in power system to enhance the damping of power system oscillations for different combinations of power system stabilizers parameters [128]. In [129], a projective control method has been addressed for coordinated control of two FACTS devices such as TCSC and Thyristor Controlled Phase Angle Regulator (TCPAR) for damping inter-area oscillations to enhance the power transfers and damping of power system oscillations. A problem of interest in the power industry is the mitigation of power system oscillations. These oscillations are related to the dynamics of system power transfer and often exhibit poor damping, with utilities increasing power exchange over a fixed network, the use of new and existing equipment in the transmission system for damping these oscillations is being considered in several literatures. The above problems are solved in literaturers [130], [131], a projective control method has been addressed for coordinated control of TCSC and SVC for enhancing the dynamic performance of a power system. In [132], a new method has been proposed for the design of power system controllers aimed at damping out electro-mechanical oscillations used for applied to the design of both PSS for synchronous generators and supplementary signals associated to other damping sources. Milanovic and Hiskens et al. suggested a new method for tuning of SVC controllers in the presence of load parameters uncertainty to enhance the damping of electro-mechanical oscillations in power systems [133]. Lie et al. presented a linear optimal controller for the designed to implement multiple variable series compensators in transmission networks of inter-connected power system is utilized to damp inter-area oscillations and enhance power system damping [134]. An application of a normalized $\mathcal{H}_\infty$ loop shaping techniques has been proposed for design and simplification of damping FACTS controllers in the linear matrix inequalities (LMI) framework in power system for enhance damping inter-area oscillation of power system [135]. In [136], a linear optimal controller has been
addressed for the design to implement multiple variable series compensators (VSCs) in transmission network of interconnected power system is utilized to damp inter-area oscillations and enhance power system damping during large disturbances. In [137], an eigen-value analysis technique is used for coordinated control of PSS and FACTS controllers to enhance damping of power system oscillations in multi-machine power system. Zhao and Jiang et al. suggested a H-infinity optimization technique for simultaneous tuning of SVC controllers design to improve the damping power system [138]. Chaudhuri and Pal et al. suggested a H-infinity damping control design optimization technique based on the mixed sensitivity formulation in a linear matrix inequality (LMI) framework for robust damping control design for multiple swing modes damping in a typical power system model using global stabilizing signals [139]. A systematic procedure for the synthesis of a Supplementary Damping Controller (SDC) for Static Var Compensator (SVC) for a wide range of operating conditions is used for testing in multi-machine power systems to enhance the damping of the inter-area oscillations, providing robust stability and good performance characteristics both in frequency domain and time domain [140]. In [141], a bifurcation subsystem based methodology has been proposed for $\mu$-synthesis power system stabilizers design in a two-area power system. The secure operation of power systems requires the application of robust controllers, such as Power System Stabilizers (PSS), to provide sufficient damping at all credible operating conditions. Recently, many researchers have investigated the use of robust control techniques including H-infinity optimization and $\mu$-synthesis techniques for developing advanced and automated procedures for power system damping controller design. A several control design techniques [142] such as the classical phase compensation approach, the $\mu$-synthesis, and a linear matrix inequality technique has been used for coordinate two PSS to stabilize a 5-machine equivalent of the South/ Southeast Brazilian power system. In [143], a Prony methods based on Prony signal analysis and incorporates both local and inter-area electro-mechanical oscillatory modes along with root locus and sequential decentralized control techniques has been used for PSSs design in multi-machine power systems. In [144], a projective control principle based on eigen-value analysis has been presented for coordinated control design of supplementary damping controller of HVDC and SVC in power system to enhance the damping of power system oscillations. A non-linear optimization programming techniques has been addressed for simultaneous coordinated tuning of PSS and FACTS controllers for damping power system oscillations in multi-machine power systems [145]. Electro-mechanical oscillations in power systems are a problem that has been challenging engineers for decades. These oscillations may be very poorly damped in some cases, resulting in mechanical fatigue at the machines and unacceptable power variations across important transmission lines. For this reason, the use of controllers to provide better damping for these oscillations is of utmost importance. A non-linear programming based algorithm has been proposed for the design of power system damping controllers for damp electro-mechanical oscillations in power systems [146]. A non-linear programming based algorithm has been proposed for the design of simultaneous coordinated tuning of PSS and FACTS controllers for damping power system oscillations in multi-machine power systems [147]. Simoes et al. presented a non-linear optimization technique is used to coordinated control of Power Oscillation Damping (POD) controllers implemented in the two TCSC of the Brazilian North-South (NS) inter-connection, in the year 1999, were solely intended to damp the low-frequency NS oscillation mode [148]. In [149], an optimization technique is used to tuning of power system stabilizers in power systems. Small disturbance stability, particularly in the context of positive damping of electro-mechanical modes or oscillations among the interconnected synchronous generator in power systems, constitutes one of the essential criteria for secure system operation. Power system stabilizers (PSSs) together with their coordination have been developed for enhancing system stability. However, the use of PSSs only may not be, in some cases, effective in providing sufficient damping for inter-area oscillations, particularly with increasing transmission line loading over long distances. Drawing on the availability of FACTS devices at present, which have been developed primarily for active- and/or reactive power flow and voltage control functions in the transmission system, more effective measures have been proposed for improving system damping. Nguyen, and Giano et al. [150]-[151] has been proposed a optimization based technique for control coordination of PSSs and FACTS controllers for Optimal oscillations damping in multi-machine power system. Damping of power system oscillations between
interconnected areas is very important for the system secure operation. Power system stabilizers (PSS) and FACTS devices are used to enhance system stability. In large power systems, using only conventional PSS may not provide sufficient damping for inter-area oscillations. In these cases, FACTS power oscillation damping controllers are effective solutions. But uncoordinated local control of FACTS devices and PSSs may cause destabilizing interactions. In [152], an optimization based approach has been suggested for power system optimization and coordination of FACTS controllers to significant transient stability improvement and effective power oscillation damping. In [153], a simulated annealing based algorithm has been addressed for PSS and FACTS based stabilizers tuning in power systems. The design problem of PSS and FACTS based stabilizes is formulated as an optimization problem. An eigen value based objective function is used to increase the system damping. Then SA algorithm is employed to search for optimal stabilizer parameters. Different control schemes have been proposed in and tested on a weakly connected power system with different disturbances loading conditions and parameter variations. The problem of poorly damped, low frequency oscillations, associated with the generator rotor swings has been a matter of concern to power engineers for along time. Damping of electro-mechanical oscillations between interconnected synchronous generators is necessary for secure system operation. These problem is improved, in [154], a fuzzy set theory based algorithms has been suggested for coordinate stabilizers so as to increase the operational dynamic stability margin of power system for TCSC and UPFC in power system environments. A fuzzy logic based method has been used for coordinated control of TCSC and UPFC in power systems to increase the operational dynamic stability margin of power system [162]. Reference [163], a load flow control technique has been proposed for coordinated control of FACTS controllers in power system for enhancing steady dynamic performance of power systems during normal and abnormal operation conditions.

8. RESULTS AND DISCUSSIONS

The following tables give summary of the paper as:

5.1 By Placement of FACTS controllers in large-scale emerging power system networks

From figure 1 it is concluded that the 39 of total literatures are reviews based on voltage stability, 02 of total literatures are reviews based on transient stability, 10 of total literatures are reviews based on rotor angle stability, and 02 of total literatures are reviews based on dynamic stability by placement of FACTS controllers in an integrated power system networks.

4. Dynamic Stability of an integrated power system networks:

In [156], a projective control method has been addressed for coordinated control of TCSC and SVC for enhancing the dynamic performance of a power system. In [157], a new real and reactive power coordination method has been proposed for UPFC to improve the performance of the UPFC control. Lei et al. suggested a sequential quadratic programming algorithm for optimization and coordination of FACTS device stabilizers (FDS) and power system stabilizers (PSS) in a multi-machine power system to improve system dynamic performance [158]. Najafi and Kazemi et al. [159] suggested an optimization based technique for coordination of PSSs and FACTS damping controllers in large power systems for dynamic stability improvement. Sebaa and Boudour et al. [160] has been suggested a genetic algorithm for coordinated design of PSSs and SVC-based controllers in power system to enhance power system dynamic stability. In [161], a fuzzy set theory based algorithms has been suggested for coordinate stabilizers so as to increase the operational dynamic stability margin of power system for TCSC and UPFC in power system environments. A fuzzy logic based method has been used for coordinated control of TCSC and UPFC in power systems to increase the operational dynamic stability margin of power system [162]. Reference [163], a load flow control technique has been proposed for coordinated control of FACTS controllers in power system for enhancing steady dynamic performance of power systems during normal and abnormal operation conditions.
5.2 By Coordination of FACTS controllers in large-scale emerging power system networks

From figure 2 it is concluded that the 15 of total literatures are reviews based on voltage stability, 04 of total literatures are reviews based on transient stability, 39 of total literatures are reviews based on rotor angle stability, and 08 of total literatures are reviews based on dynamic stability by coordination of FACTS controllers in an integrated power system networks.

Figure 2 By coordination of FACTS controllers in large-scale emerging power system networks

5.3 By Placement and Coordination of FACTS controllers in large-scale emerging power system networks

From figure 3 it is concluded that the 54 of total literatures are reviews based on voltage stability, 06 of total literatures are reviews based on transient stability, 49 of total literatures are reviews based on rotor angle stability, and 10 of total literatures are reviews based on dynamic stability by placement and coordination of FACTS controllers in an integrated power system networks.

Figure 3 By placement and coordination of FACTS controllers in large-scale emerging power system networks

From figure 3 finally it is also concluded that the maximum research work carryout from voltage Stability and rotor angle stability by placement and coordination of FACTS controllers in an integrated power system networks.

9. CONCLUSIONS

This report has addressed the issue of stability definition and classification in power systems from a fundamental viewpoint and has examined the practical ramifications of stability phenomena in significant detail. A precise definition of power system stability that is inclusive of all forms is provided. A salient feature of the report is a systematic classification of power system stability, and the identification of different categories of stability behavior. Linkages between power system reliability, security, and stability are also established and discussed. The report also includes a rigorous treatment of definitions and concepts of stability from mathematics and control theory. This material is provided as background information and to establish theoretical connections.
This paper has also addressed a survey on enhancement of power system stability such as rotor angle stability, frequency stability, and voltage stability by using different FACTS controllers such as TCSC, SVC, SSSC, STATCOM, UPFC, and IPFC in an integrated power system networks. Also this paper discussed the current status of the research and developments in the field of the power system stability such as rotor angle stability, frequency stability, and voltage stability enhancement by using different FACTS controllers in an integrated power system networks. Authors strongly believe that this survey article will be very much useful to the researchers for finding out the relevant references in the field of enhancement of power system stability by using different FACTS controllers in an integrated power system network.

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