Inter-area oscillations in Inter-Connected Power System: A review

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Abstract-Power system stability is the major issue to the interconnected power system.With growing electric power demand, the inter-area low frequency oscillations become a biggest problem for power system engineers and often suffer from poor system damping. This paper give brief explanation of power system different type of stabilities problem, black outs in the world, different topology. Furthermore, the optimization strategies for the damping controller are reviewed along with the benefits and limitations, current issues and challenges, and recommendations. All the highlighted insights of this paper will hopefully lead to increasing efforts toward the development of an advanced optimized damping controller for future high-tech multi-machine power systems.

***Index Terms*—Power system stability, inter-area oscillations, optimization, PSS, Damping controller.**

I. INTRODUCTION

Power system stability is the capability of an electric powersystem to regain operating equilibrium after being subjectedto a physical disturbance. Power system stability is themost important issue in achieving secure and reliable operation[1], [2]. The demand for electricity is increasingphenomenally because of technological complexity and innovations.This persistent demand leads to the presence of interconnectedpower systems through long transmission lines.Such power systems are operated around their maximumlimits to meet the growing demands. Therefore, the safeoperation of power systems is an ultimate challenge againstvarious small or large disturbances in power networks. Disturbancesin power systems may lead to an increase in unwantedpower system oscillations [3]. If these oscillations are notdamped completely, then power system stability may faceserious threats [4]. The consequences of instability may come in the form of frequency disturbances, transients, electrostatic discharges, harmonics, electromagnetic interferences, and low power factors, which result in data malfunction, loss of information, damage to sensitive equipment, overheating of cables and devices, and efficiency reduction in electric machines [5]_[7]. The presence of power system oscillations also reduces the total power transfer capacity of existing transmission lines [8], [9]. Therefore, addressing power system oscillations is a global concern. An optimum solution is needed for the controller design of multi-machine power systems to control nonlinear loads, converters, environmental impacts, and power quality issues. In particular, various automated damping schemes areundertaken to meet the required damping for power systemstability. The installation of a power system stabilizer (PSS) is a primary damping scheme [10]. Currently, most generators are equipped with PSS. However, a PSS may not be able to provide the required damping for the smooth operation of a multi-machine power system. In such cases, additional damping schemes by means of a flexible alternating current transmission system (FACTS) are considered [11], [12]. In the case of multi-machine power systems, stability is affected mainly because of the presence of inter-area modes of oscillations. The application of FACTS-based damping schemes is becoming popular in such modes [13], [14]. The damping performance of FACTS devices depends solely on the proper design of their controllers [15], [16]. However, the installation of multiple damping schemes may cause destabilization of the system because of the interaction of the controllers if the designs are not coordinated properly [17], [18]. Therefore, designing damping controllers to damp oscillations successfully in power systems is a challenge. The design of damping controllers is an optimization problem, which is solved using various optimization techniques. In particular, the eigenvalue-based stability single-machine infinite-bus systems analysis is used to attain the optimum design of damping controllers [19], [20]. The robust design of controllers is the only possible solution against oscillations in power systems to ensure safe operation. However, the nature of oscillations in power systems is complex [21]. Therefore, robust design is ensured by inspecting damping performance over different modes of oscillations [22], [23]. In general, the modes of oscillation are identified on the basis of their frequencies [24]. For overall system stability, the steps of the design procedure are crucial to achieving optimum damping. Usually, the design can then be verified with transient stability analysis for different system disturbances. Therefore, the proper design of damping controllers can be the solution to the stability problem in complex multi-machine power systems. The design of damping controllers is the primary step undertaken to ensure the stability of multi-machine power systems. The appropriate selection of controller parameters is a design challenge [25], [26]. In the case of multi-machine power systems, the design problem becomes complex because of the many parameters that need to be optimized. In particular, stability analysis is conducted in linearized power systems on the basis of the location of system eigenvalues in the complex s-plane. In this method, the optimization of damping controllers in a linearized model of the power system is associated with two major tasks, namely, (i) the formulation of the objective function and (ii) the selection of the optimization technique and its implementation.

Over the past years, various studies of controller design have been conducted [9], [27]_[30]. In these studies, the authors considered different approaches to formulating the objective function. The objective function is an important part of controller design; therefore, its inappropriate formulation may significantly contribute to achieving poor and insufficientdamping by the applied damping schemes. Therefore, the objective function is a foremost part of the robustdesign of damping controllers. No research has compared the performances of different formulations of the objective function. Prior to this issue, identifying the best approach to formulating the objective function for a rigorous design that maximizes the stability of multi-machine power systems is necessary. The application of heuristic algorithms is the most common and widely accepted optimization technique for the design of damping controllers [26], [31], [32]. Many types of studies using various traditional heuristic algorithms have been conducted. In general, the performance of heuristic algorithms is a problem-oriented application. Many heuristic algorithms have been applied in single-machine infinite-bus systems (SMIB) and small-sized multi-machine systems to investigate the damping performance [33], [34]. Investigating the variation in design performance occurring with the increase in problem dimensions (large power systems) is important. In several cases, authors considered a reduced number of controllers and optimizing parameters to avoid design complexities [35]. The single-convergence curve was used to measure the performance of the proposed heuristic algorithms [36]. The path of convergence changed each time because heuristic algorithms use stochastic techniques to derive solutions. Therefore, comparing the performances of algorithms is insufficient. These issues indicate a lack of comprehensive analysis for damping controller design in multi-machine power systems. In the case of such power systems, the numbers of optimizing parameters for damping controllers are relatively large and the complexity of the optimization problem increases significantly. The design of damping controllers in power systems is a multimodal optimization problem. This type of optimization problem is complex and difficult to solve. In this case, traditional algorithms do not perform well because their performance deteriorates with an increase in problem dimension. In addition, the tendency to become trapped in the local minima is the most common pitfall of traditional heuristic algorithms [37], [38]. In such cases, the optimum solutions are not easily obtained, consequently preventing the achievement of robust damping by the applied damping schemes. This review provides a detailed overview of power system oscillations and damping controllers to enhance future research and development in designing efficient damping controllers for multi-machine power systems. The review discusses the power system oscillation, its principle, and classifications. The overview of various damping schemes and controllers for improving the stability of power system are comprehensively explained. The controller design is streamlined by two distinctive works; finding the best objective function used in the linearized method and developing the optimization technique. A review of various approachesto formulate the objective functions are summarized and discussed. Also, the review of the optimization techniques considered in past researches is highlighted with their advantages and disadvantages. Finally, the review delivers some recommendations to enhance the efficiencyof future damping controllers as well as proposed future studies for further investigations.

II. METHODOLOGY

The review focuses on the improvement of dampingcontroller performance for the multi-machine power systemstability using optimization techniques. To achieve the target,the review uses Scopus scientific database based books, journals,and conference proceedings to search for the suitablearticles within scope and target. The relevant literature wasselected by analyzing the title, abstract, keywords, papercontents and results. The selection of articles was basedon impact factor, citation, and review process. Accordingly,the articles published after 2010 were chosen for citation.The obtained results were arranged into six groups. Firstly,the reviews start with the explanation of power systemstability and oscillation, including rotor dynamics. Secondly,the different types of damping schemes of power systemsare explored. In addition, damping controllers, linearizationtechniques, toolbox, and eigenvalue are comprehensivelydiscussed. Thirdly, construction of objective functionsincluding single objective function and multi-objective functionis described. Fourthly, the well-known optimization techniquesfor damping controller design and their benefits andlimitations are highlighted. Fifthly, a brief discussion of thecurrent issues and challenges in power system oscillations,damping controllers, and their optimization is presented.Lastly, the review provides some key suggestions and futuredirections for further development on damping oscillation inmulti-machine power systems.

III. POWER SYSTEM STABILITY AND OSCILLATION

The stability of an interconnected power system is the primary concern in maintaining its secure operation. The fundamental requirement behind the interconnection of the power system is to synchronize all connected generators. In addition, the persistent demand for electricity using the existing infrastructure ensures that the power system operates at its maximum capacity. These issues have motivated power engineers and researchers to deal with inherited power system oscillations and stability challenges. Power system stability can be classified into three major categories, as shown in Fig. 1 [39], [40]. This study is mainly concerned with power system oscillations and their associated rotor angle stability issues.

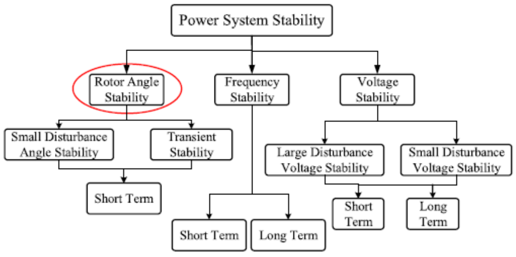

Figure 1: Classification of power system stability.

a) Power System Oscillations

Rotor angle stability is the capability of a synchronous generatorto remain in synchrony after being subjected to an oscillation [41], [42]. Rotor angle stability problems may arise from continuous small oscillations (load changes) or largeoscillations (natural disasters or severe system faults).Power system oscillation is the fundamental phenomena of synchronous generators, in which the generated output power varies as the rotors oscillate with synchronous speed. Power system oscillation is an inherited property of an interconnected power system caused by the dynamic nature of synchronous machines [43]. Any incident (small or large disturbance) in the power system can initiate power system oscillations in the form of some consecutive events occurring in a synchronous generator, as shown in Fig. 2 [44], [45].

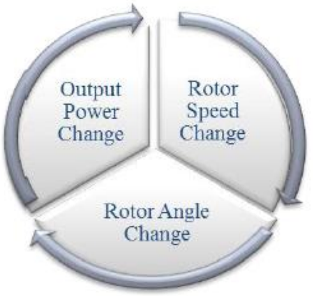

Figure 2: Consecutive events in electromechanical oscillations.

Under unfluctuating conditions, the balance between mechanical and electromagnetic torques of a synchronous generator and the rotor speed remains at synchronous speed. When the equilibrium is upset because of any perturbation, the speed of the rotor changes (accelerate or decelerate) from its synchronous speed in response. The change in rotor speed leads to a change in relative rotor angle. The change in rotor angular position leads to a change in generated output power according to the power angle characteristics [44]. When the output power changes, the rotor changes its speed again; consequently, the rotor angle also changes again. These consecutive events are well known as the oscillations in power systems. These oscillations arise due to the imbalance between the electrical and mechanical torques of synchronous generators [45], [46]. Therefore, such oscillations are also known as electromechanical oscillations. The frequency of these electromechanical oscillations is usually 0.2_3 Hz [47]. Generally, electromechanical oscillations are characterized visually by drawing the time vs. rotor speed deviation, as shown in Fig. 3.

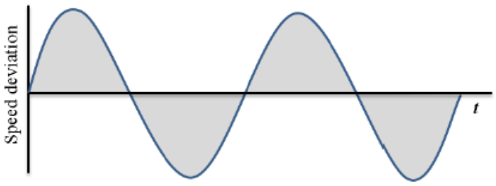

Figure 3: Visualization of power system oscillation

In an interconnected power system scenario, generators from one region are connected to generators of other regions to form a national or an international grid of power lines. In this case, the transmission lines are called tie lines when two different systems are connected via the transmission lines. The nature of power system oscillations is complex.

In view of fundamental analysis, understanding the various modes of oscillation occurring in the system is important. In general, power oscillations are classified into two types [47], namely, (i) local area modes of oscillation and (ii) inter-area modes of oscillation. Local area modes of oscillation oscillate the nearby generators or the generators in the same region. Thus, the local area modes of oscillation affect the generators in the same region or nearby regions. By contrast, the inter-area modes of oscillation are the oscillations in the coherent generators of different regions connected through long tie lines. The local area modes of oscillations are small cycle oscillations that have high frequencies in the range of 0.8_3.0 Hz [47]. The inter-area modes of oscillation are long cycle oscillations that have low frequencies in the range of 0.2_0.7 Hz [48]. Inter-area oscillations can originate from heavy power transfers across weak tie lines. This type of oscillation in the power system limits the power transfer capacity of the tie lines between the regions containing the group of coherent generators [47]. The presence of inter-area modes is typical for a power system with long-distance tie lines [49]. Compared with local modes, inter-area modes are dangerous because they convey oscillations that affect the generators of other regions. Thus, inter-area oscillations are considered the most catastrophic event in power system stability [50]. These oscillations may last long, and detecting its presence, which may subsequently destabilize the system, is difficult in several cases [47].

Oscillations in the power system may affect the stability of entire power systems. If the oscillations are not damped successfully, then power outages may occur and millions of people can be affected. The Western US/Canada power outage that occurred on 10 August 1996 is an example [47]. The outages were due to the excessive power flow through the US/Canada interconnection and the sequence of small disturbances.

Oscillations in synchronous generators are the core phenomena behind the collapse of power systems [51]_[53]. Analyzing the historical incidents that have affected daily living is necessary to understand the effect of power system oscillations. For an overview, a list of the major power outages that have occurred globally are listed in Table 1 along with the tentative number of affected people [54], [55]. Understanding the potential severity that can result from not undertaking proper steps is important to protect the system from collapsing. Numerous studies have been conducted to protect the system stability from the dark consequences of power system oscillations. Furthermore, such studies are assumed to continue extensively to improve power systemstability.

Table-1: Major power outage caused by power system instability

Year	Date	Affected Country	Affected people(millions)
1965	9 November	United states, Canada	30
1978	18 March	Thailand	40
1999	11 March	Brazil	97
2001	2 January	India	230
2003	28 September	Italy, Switzerland, Austria, Slovenia and Croatia	55
2005	18 August	Indonesia	100
2009	10-11 November	Brazil and Paraguay	87
2012	30-31 July	India	620
2014	1 November	Bangladesh	150
2015	26 January	Pakistan	140
2016	7 June	Kenya	10

Rotor Dynamics

The angle between the resultant magnetic field axis and the rotor axis is called the power or torque angle. The relative position between these two axes remains unchanged under normal operating conditions. However, relative motion is initiated during any disturbance and the rotor starts accelerating or decelerating with respect to the synchronously rotating air gap, the mathematical expression of which explains that this relative motion is defined as the swing equation. The stability of the generator will be restored if the rotor runs at synchronous speed again after the oscillation occurs. The original position of the rotor will be retained if the disturbance does not cause any variation in power. Nevertheless, the rotor will operate at a new torque angle relative to the synchronously revolving field if sudden oscillations arise from any abnormality in load, generation, or network conditions [48], [49]. A combined Phasor diagram of a two-pole cylindrical rotor generator is illustrated in Fig. 4 to aid in understanding the significance of the power angle.

A synchronous generator rotates at synchronous speed w_{sm} and generates the electromagnetic torque T_e and driving mechanical torque T_m. the steady-state condition without losses can be expressed as follows:

$$T_m = T_e \tag{1}$$

Any disturbance will cause instability, which induces the rotor to either accelerate ($T_m > T_e$) or decelerate (T > Tm) as follows:

$$T_a = T_m - T_e \tag{2}$$

Equation (2) can be expressed in terms of the law of rotation with the effect of the moment of inertia 'J' ignoring damping torque and frictional losses.

$$j\frac{d^2\theta_m}{dt^2} = T_a = T_m - T_e \tag{3}$$

Where $\theta_m$presents the angular displacement of the rotor with respect to the stationary reference axis of the stator. Angular reference is selected relative to a synchronously rotating reference frame moving with constant angular velocityw_{sm}, that is,

$$\theta_m = w_{sm}t + \delta_m \tag{4}$$

Where $\delta_m$is the rotor position before the disturbance at time $t = 0$, measured from the synchronously rotating reference frame. A derivative of Equation (4) yields the rotor angular velocity as follows:

$$w_m = \frac{d\theta_m}{dt} = w_{sm} + \frac{d\delta_m}{dt} \tag{5}$$

The rotor acceleration is expressed as follows:

$$\frac{d^2\theta_m}{dt^2} = \frac{d^2\delta_m}{dt^2} \tag{6}$$

Substituting Equation (6) into Equation (3), we derive the following expression:

$$j\frac{d^2\delta_m}{dt^2} = T_m - T_e \tag{7}$$

Multiplying Equation (7) with $w_m$results in the following expression:

$$jw_m\frac{d^2\delta_m}{dt^2} = w_mT_m - w_mT_e \tag{8}$$

Equation (8) can be expressed in terms of power, which is the product of the multiplication of torque and velocity, as follows:

$$jw_m\frac{d^2\delta_m}{dt^2} = P_m - P_e \tag{9}$$

The quantity $jw_m$is called the inertia constant and is denoted by M, which is related to the kinetic energy of the rotating massesW_k, as follows:

$$W_k = \frac{1}{2}jw_m^2 = \frac{1}{2}Mw_m \tag{10}$$

or

$$M = \frac{2w_k}{w_m} \tag{11}$$

M does not keep constant as long as the rotor is not rotating at synchronous speed. Given that $w_m$does not vary in large number before the system becomes unstable,M is validated at the synchronous speed and is selected to remain unchanged, that is,

$$M = \frac{2w_k}{w_{sm}} \tag{12}$$

The swing equation in terms of inertia constant becomes

$$M\frac{d^2\delta_m}{dt^2} = P_m - P_e \tag{13}$$

Equation (13) describes the behavior of the rotor dynamics, which can be used to explain the rotor damping oscillation in the power system.

IV. TYPES OF DAMPING SCHEMES AND STABILITY ANALYSIS

Given that incidents of power system oscillations occur without warning, automated control schemes are implemented to damp those oscillations if detected through proper input signals. In this section, various schemes and modeling approaches used to enhance system damping over oscillations are categorized and discussed. Over the past years, numerous studies of different damping schemes have been conducted to suppress oscillations in the power system. The damping schemes may be classified broadly into three categories, namely, PSS-based damping schemes, FACTS-based damping schemes, and coordination control schemes.

a) Power System Stabilizer (PSS)

In 1969, De Mello and Concordia introduced the concept of PSS [50]. PSS is the primary and cost-effective damping scheme for power system stability. A schematic of a synchronous generator with PSS is shown in Fig. 4 [51], [52]. According to the theory of synchronous machines, the generated output power can be controlled by controlling the excitation voltage. The purpose of installing the PSS is to provide a supplementary input signal to the excitation system of the synchronous generator. PSS bringsan additional synchronizing torque in phase with speed deviation. As a result, the increasing oscillations are damped and the system stability is restrained. Various researchers explained power system stability by means of installing and designing PSS for single-machine [53], [54] and Multimachine power systems [55], [56]. The damping performance of the PSS scheme depends on its proper design [57]. Usually, the proper design of the PSS is effective not only in damping local modes of oscillation but also in damping inter-area modes of oscillation [58], [59].

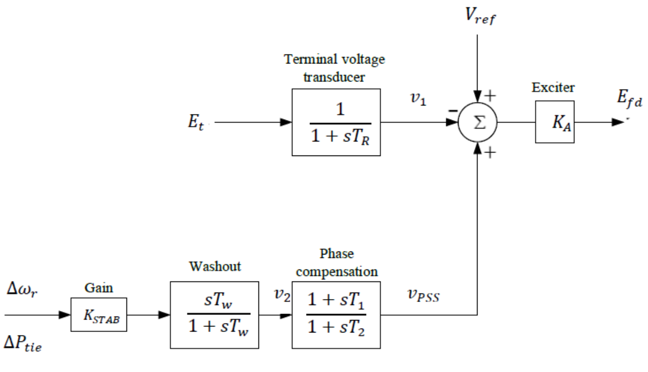

Figure 4: PSS controller with excitation system of synchronous generator

b) Damping Controller

The damping controller is the key player in the damping scheme of the power system. The damping controller decides the switching control of damping schemes. In prior literature, different types of controllers have been proposed for PSS-based and FACTS-based damping schemes. Fuzzy controllers and artificial neural network (ANN) controllers were employed in, [26], [60], and [61]. In general, fuzzy and ANN controllers are highly complex types of controllers that are difficult to implement in a practical scenario. Furthermore, proportional-integral-derivative (PID) controllers have been illustrated for damping power system oscillations in interconnected power systems [62], [63]. However, PID controllers are not preferred because of their high-order derivative terms and lack of assurance of stability. Since 1991, lead-lag controllers have been the most popular and dominant type of controllers for damping oscillations in the power system. The extensive application of lead-lag controllers in prior literature indicates its considerable popularity and utility [64]_[65]. The preference of utility companies and researchers for lead-lag controllers can be attributed to the advantages of cost-effectiveness, assurance of stability, and ease of use [66], [67]. The structures of the PSS controller [68], [69]. These controllers are identical, as shown in Figs.5.

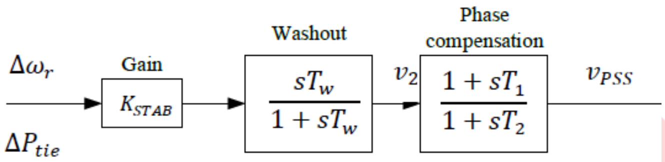

Figure 5:Lead-lag PSS controller.

System Linearization Technique and Toolbox

In particular, the design process of damping controllers is investigated under the power system stability study [70]. The power system consists of several dynamic elements, and the modeling of these elements is the core steps for conducting the stability study. A dynamic model of power system includes linear/nonlinear differential and algebraic equations. Since the early 1970s, linear analysis has been used to investigate the dynamic behavior of a power system [71]. The dynamics of a power system can be represented by a set of nonlinear ordinary differential equation (ODE) as follows:

$$\dot{x} = f(x,u)$$
$$y = g(x,u) \qquad (7)$$

where f and g are nonlinear functions, x is the state vector, u is the input vector, and y is the output vector expressed as follows:

$$x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{n-1} \\ x_n \end{bmatrix}; u = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_{n-1} \\ u_p \end{bmatrix}; y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{n-1} \\ y_q \end{bmatrix}; f = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_{n-1} \\ f_n \end{bmatrix}; g = \begin{bmatrix} g_1 \\ g_2 \\ \vdots \\ g_{n-1} \\ g_q \end{bmatrix}$$

If x_0 and u_0 are the equilibrium states and input vectors, respectively, around which the linearized model is to be obtained, then

$$x_0 = f(x_0, u_0) = 0 \qquad (8)$$

If the system is perturbed from its equilibrium by a small deviation (Δ), then

$$\dot{x} = \dot{x}_0 + \Delta\dot{x} = f[(x_0 + \Delta x), (u_0, \Delta u)] \qquad (9)$$

If the nonlinear function f (x; u) is expanded into Taylor's series around x_0 and u_0. The final linearized state space equations can be written as follows:

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du \qquad (10)$$

where A is the state matrix, B is the input matrix, C is the output matrix, and D is the feed forward matrix.

Thus, the final linearized equation (Equation (10)) is known as linear time-invariant (LTI) state-space model. Generally, the LTI state-space model is formed by linearizing the nonlinear ODE around an operating point to a set of coupled first-order linear differential equations, as shown in Equation (10). The modeling of the power system is inherent in proper and precise mathematical presentations [72]. Therefore, the modeling of the power system is monotonous and complex work. However, several toolboxes are available for minimizing the overall burden of complex modeling. MATLAB/SIMULINK based power system block set and power system analysis toolbox have been used to design coordinated controllers in [73] and [74], respectively. Moreover, a power system toolbox (PST) developed in the MATLAB environment by Rogers [47] is a comprehensive tool widely used to analyze power system oscillations. The PST has been used extensively by previous researchers in designing damping controllers [73], [75], [76]. The PST comprises two models of the power system, namely, the linearized model in LTI state-space form and the nonlinear model for time-domain simulation analyses.

c) Eigenvalues and Stability Analysis

The locations of eigenvalues on the complex s-plane are associated with the stability of a linearized power system. The system stability is determined by analyzing the eigenvalues ($\lambda_i = (\sigma_i + j\omega_i)$) obtained from state matrix (A) of the LTI state-space model. The eigenvalues of the state matrix (A) are derived as follows:

$$\lambda_i = eig(A) \qquad (11)$$

where $i = 1,2,3 \ldots \ldots \ldots n$. n is the total number of eigenvalues, which is also equal to the number of state variables in the system. Here, eig is the built-in MATLAB function used to determine the system eigenvalues. According to the theory of advanced control system, system stability can be determined easily on the basis of the location of eigenvalues on the s-plane (complex plane).

V. REVIEW OF THE OPTIMIZATION TECHNIQUES FOR DAMPING CONTROLLER DESIGN

Over the past decades, various optimization techniques have been used to optimize the controller parameters for damping schemes [77], [78]. Optimization techniques may be categorized broadly into four, namely, (i) conventional, (ii) deterministic, (iii) heuristic, and (iv) hybrid techniques.

HEURISTIC TECHNIQUES

Heuristic optimization techniques are global optimization techniques that use the stochastic (randomization) method to discover the solution. A heuristic technique is a process or set of rules that learns or finds a solution through trial and error. The improved version of heuristic techniques is known as met heuristic algorithms. Most heuristic algorithms were developed on the basis of nature-inspired concepts. An advantage of the heuristic algorithm is that it does not require predicting the initial solution similar to the deterministic techniques. This type of optimization is more flexible and efficient for robust optimization than deterministic techniques. Heuristic methods are robust compared with conventional and deterministic optimization techniques in solving a variety of optimization problems that include nonlinear, non-differentiable complex problems. The application of heuristic algorithms in robust damping controller design has been observed since the past decades and is described as follows:

a) Genetic Algorithm

Genetic algorithm (GA) was proposed for the simultaneous design of multi-machine PSS in [69]. GA was recommended to formulate the multi-objective function for robust damping performance [67]. Another research was conducted using GA to design the coordination control of PSS and TCSC [79]. However, researchers have discovered some deficiencies of GA, such as premature convergence caused by the local minimum stagnation problem. Various modification have been proposed by many authors to overcome the limitations of GA [80]. For the multi-machine power system, the performance of GA deteriorates with an increase in problem dimension. An improved real immune algorithm with population management (RIAPM) was introduced to deal with a large number of parameters optimized in the coordination control of PSS and SVC and thus overcome this problem [81]. Real-coded GA has also been presented for the analysis and design of the SSSC-based damping controller [82]. GA requires the high computational capacity to solve complex optimization problems, such as the design of multi-machine damping controllers. Recently, breeder GA for PSS optimization has been proposed to eliminate the various shortcomings of GA by introducing an adaptive mutation that incorporates the concepts of evolution and Darwin's theory of selection. The effectiveness of GA is affected by the choice of the range of search space. Differential evolutionary algorithm (DEA).

b) Particle Swarm Optimization

Particle swarm optimization (PSO) is a population-based metaheuristic optimization technique that mimics the social behavior of a flock of birds or a school of fish during their movement. PSO can solve the complex multimodal optimization problem. PSO has been presented in many kinds of literature for damping controller design [80], [81], [82]. However, PSO has several additional control parameters, and their selection significantly affects the final solution. Moreover, local minimum stagnation is a common problem of PSO [83]. Modification of PSO has been proposed to improve the damping performance in the power system [70].

VI. CONCLUSION AND RECOMMENDATIONS

Electromechanical oscillations in the electric power system are a problem that causes safety issues, limits power transmission capacity, and leads to the collapse and blackout of the entire interconnected system. Therefore, an adequate damping controller is of utmost importance in solving the oscillation issues. Multiple damping controllers, such as PSSs and PODs, have been developed by formulating objective functions and optimization techniques to enhance system dynamic stability and increase system operating flexibility. However, damping controller development in a complex multi-machine power system is a constraint-based multimodal optimization problem, which is difficult to resolve using conventional optimization algorithms. To address these issues, this review introduces the principles and classifications of power system oscillations inherited in the complex power system. Commonly used types of damping schemes and controllers have been discussed with regard to their advantages and limitations. From the rigorous review, we noted that FACTS-based SVC and TCSC damping controllers are commonly employed to achieve adequate damping throughout oscillations in the system. Lead-lag controllers are the most preferred types because of their robust performance of damping schemes. In this review, the system linearization technique is presented and PST is specified as the commonly used and appropriated toolbox for simplifying the complex modeling burden. The different eigenvalue-based approaches for objective function formulation are reviewed and summarized. The discussion concludes with the requirement of comparative study for different formulation approaches. Inaddition, various optimization techniques generally applied for controller parameter optimization are categorized and discussed in terms of their advantages and limitations. Finally, the major limitations ofthe existing design approaches are discussed. At the end of the review, the current issues and challenges are highlighted. In light of these concerns, this review provides some recommendations for ensuring the development of efficient damping controllers for future multi-machine large power systems in solving the existing problems.

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