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Artificial Intelligent Based Damping Controller Optimization for the Multi-Machine Power System: A Review

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ABSTRACT Power system oscillation is a major threat to the stability of an interconnected power system. The safe operation of a modern power system is largely related to the success of oscillation damping. However, damping controller development is a constraint-based multimodal optimization problem, which is relatively difficult to resolve utilizing conventional optimization algorithms. This paper presents a critical examination of different damping schemes and a stability analysis of a damping controller to solve these existing problems and enhance the performance of a multi-machine power system. This paper also describes different approaches used to derive the objective function formulation. Consequently, a comprehensive review of the optimized objective functions and techniques is explained on the basis of their topologies, types, execution times, control difficulties, efficiencies, advantages, and disadvantages to develop intelligent damping controllers for the systems. 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 Damping controller, optimization, objective function, oscillations, power system stabilizers (PSS), flexible alternating current transmission system (FACTS).

I. INTRODUCTION

Power system stability is the capability of an electric power system to regain operating equilibrium after being subjected to a physical disturbance. Power system stability is the most important issue in achieving secure and reliable operation [1], [2]. The demand for electricity is increasing phenomenally because of technological complexity and innovations. This persistent demand leads to the presence of interconnected power systems through long transmission lines. Such power systems are operated around their maximum limits to meet the growing demands. Therefore, the safe operation of power systems is an ultimate challenge against various small or large disturbances in power networks. Disturbances in power systems may lead to an increase in unwanted power system oscillations [3]. If these oscillations are not damped completely, then power system stability may face serious 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 are undertaken to meet the required damping for power system stability. 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 insufficient damping by the applied damping schemes. Therefore, the objective function is a foremost part of the robust design 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 approaches to 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 efficiency of future damping controllers as well as proposed future studies for further investigations.

II. METHODOLOGY

The review focuses on the improvement of damping controller performance for the multi-machine power system stability using optimization techniques. To achieve the target, the review uses Scopus scientific database based books, journals, and conference proceedings to search for the suitable articles within scope and target. The relevant literature was selected by analyzing the title, abstract, keywords, paper contents and results. The selection of articles was based on 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 system stability and oscillation, including rotor dynamics. Secondly, the different types of damping schemes of power systems are explored. In addition, damping controllers, linearization techniques, toolbox, and eigenvalue are comprehensively discussed. Thirdly, construction of objective functions including single objective function and multi-objective function is described. Fourthly, the well-known optimization techniques for damping controller design and their benefits and limitations are highlighted. Fifthly, a brief discussion of the current issues and challenges in power system oscillations, damping controllers, and their optimization is presented. Lastly, the review provides some key suggestions and future directions for further development on damping oscillation in multi-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.

A. POWER SYSTEM OSCILLATIONS

Rotor angle stability is the capability of a synchronous generator to remain in synchrony after being subjected to an oscillation [41], [42]. Rotor angle stability problems may arise from continuous small oscillations (load changes) or large oscillations (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].

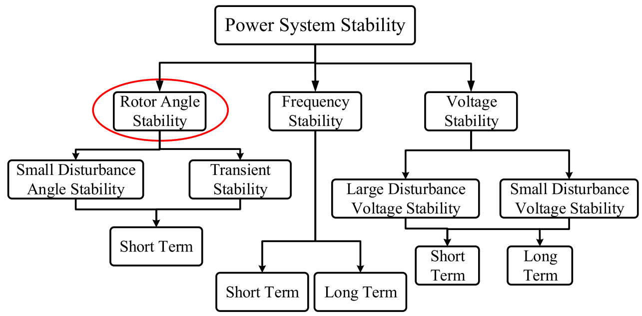

FIGURE 1. Classification of power system stability.

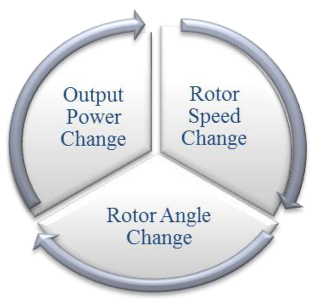

FIGURE 2. Consecutive events in electromechanical oscillations.

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.

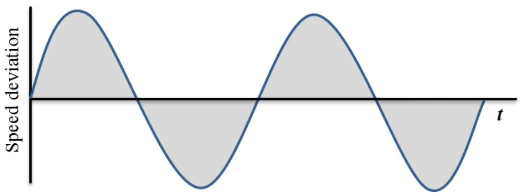

FIGURE 3. Visualization of power system oscillation.

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 system stability.

TABLE 1. Major power outages 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

B. 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.

Fig. 4 shows that the angle between the resultant air gap mmf F_{sr} and the rotor mmf F_r is known as the angle δ_r. The angle between stator voltage E_{sr} and no-load generated emf E is also presented as δ_r. The power angle δ is the angle between no-load generated emf E and terminal voltage V if leakage flux and armature resistance are considered [56].

A synchronous generator rotates at synchronous speed w_{sm} and generates the electromagnetic torque T_e and driving

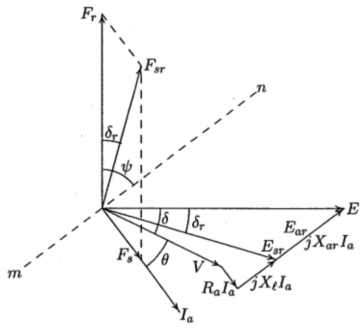

FIGURE 4. Phasor diagram of two-pole cylindrical rotor generator.

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 ($T_e > T_m$) 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 Jignoring damping torque and frictional losses.

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

where θ_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 velocity w_{sm}, that is,

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

where δ_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:

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

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 masses W_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.

C. RENEWABLE ENERGY INTEGRATION PROBLEMS

The implementation of renewable energy resources (RESs) in the form of distributed generators and microgrids in grid networks has attracted considerable attention and become a topic of global research in recent years because of its capability to address global warming, climate change, and GHS issues [57], [58]. Furthermore, the increasing fuel prices and reduction in fossil fuel reserves have urged the necessity of executing RESs, which are deemed a promising alternative to conventional power plants because of their clean and infinite energy sources. However, the application of RESs to the electricity grid is a challenging task [59], [60]. Solar PV and wind energy can add a significant amount of energy to the grid; however, their performance in delivering safe and high-quality supply has become a concern because of the lack of reliability, regularity, stability, and efficiency [61]. Several key issues include synchronization to the grid, turbine design, grid congestion, efficiency and reliability of grid interference, operational restriction, protection, voltage stability, power quality, and PSS; most importantly, developing a robust controller for the appropriate integration of RESs needs to be considered for reducing oscillation and improving reliability, performance, and system inertia [62], [63]. Nevertheless, designing an appropriate controller is a laborious task. Therefore, the proper modeling of generators, including sizing, placement [64], [65] and controller optimization and dynamics, must be adopted [35].

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, as shown in Fig. 5. In the subsequent sections, these categories are discussed along with their previous applications in power systems.

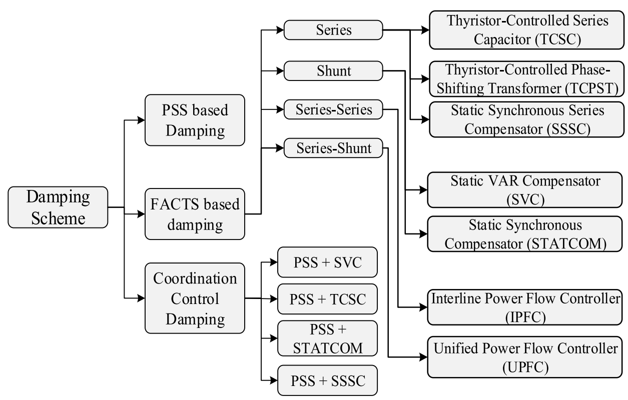

FIGURE 5. Types of damping schemes used for power system oscillations.

For a quick overview, Table 2 summarizes the basic purposes of different damping schemes and their weaknesses.

TABLE 2. Comparison of different types of damping schemes.

Damping scheme type	General damping purposes	Weakness
PSS [66]	To provide damping over local modes of oscillations	Performance is relatively weak over inter-area modes of oscillations for a long transmission line system
FACTS [67]	To enhance damping over inter-area modes of oscillations	Actual damping cannot be provided against all local area modes of oscillations.
PSS + FACTS [68]	To ensure damping against local area and inter-area modes of oscillations	Improperly coordinated design of controllers may affect system stability by negative damping

A. POWER SYSTEM STABILIZER (PSS)

In 1969, De Mello and Concordia introduced the concept of PSS [69]. PSS is the primary and cost-effective damping scheme for power system stability. A schematic of a synchronous generator with PSS is shown

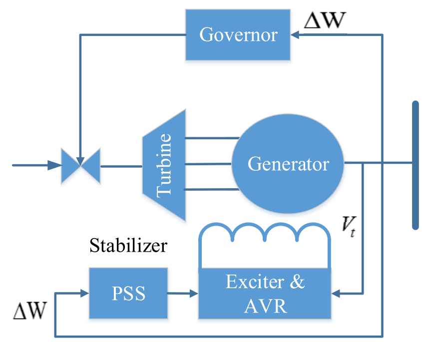

FIGURE 6. PSS controller with excitation system of synchronous generator.

in Fig. 6 [70], [71]. 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 brings an 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 [72], [73] and multi-machine power systems [74], [75]. The damping performance of the PSS scheme depends on its proper design [76]. 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 [69], [76].

B. FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEM (FACTS)

The modern power system becomes large through the interconnection of different regions. In several cases, the interconnections are required via long transmission lines (thousands of kilometers). Thus, the oscillation dynamics of the modern power system are complex in nature. In particular, the inter-area modes of oscillations are not damped easily by the implementation of PSS only. This issue requires the attention of modern control that is based on power electronics. FACTS are power-electronic-based fast-acting devices adopted as additional damping schemes to enhance controllability and power transfer capability [77]. The concept of FACTS was proposed by the Electric Power Research Institute in the late 1980s. The application of FACTS in suppressing oscillations is not its primary function, although the damping function has attracted interest from the academia and industry [78]. Since then, various studies have been conducted to investigate the usability of FACTS in power systems [67], [79]. New and efficient methods have been found through the invention of FACTS devices to manage the power flow and improve the dynamic stability of the system.

Over the years, various FACTS devices have been introduced to improve system damping over oscillations.

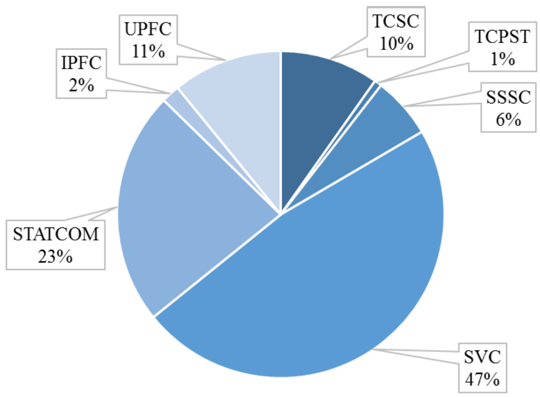

FIGURE 7. Publication distribution on application of various FACTS devices.

Fig. 7 shows the distribution of publications for various FACTS devices from 2002 to 2014.

In general, FACTS devices are categorized into four types in terms of the way they are connected to a network [80], [81]. These categories are series FACTS devices, such as thyristor-controlled series capacitor (TCSC), thyristor-controlled phase-shifting transformer (TCPST), and static synchronous series compensator (SSSC); shunt FACTS devices, including static VAR compensator (SVC) and static synchronous compensator (STATCOM); combined series–series FACTS devices, such as interline power flow controller (IPFC); and combined shunt–series FACTS devices, such as unified power flow controller (UPFC). As shown in Fig. 7, the publication distribution of SVC is approximately 47%, which is the highest percentage in the research on shunt FACTS devices. Therefore, SVC is the most widely used shunt FACTS device. By contrast, the publication distribution of TCSC is approximately 10%, which is the highest percentage in the research on series FACTS devices, as shown in Fig. 7. Therefore, TCSC is the most popular series FACTS device. The functional diagram of various FACTS devices is shown in Fig. 8 [82]–[84].

The basic functionality of FACTS devices is the proper firing of the thyristor gate; as a result, it injects or absorbs reactive power by adjusting the reactor stacks or capacitor banks and designing the controller of FACTS devices. The damping performance using FACTS depends on the proper design of its power oscillation damper (POD) controllers [85].

C. COORDINATION CONTROLS OF PSS AND FACTS

Currently, nearly all synchronous generators are equipped with PSS. Moreover, FACTS-based schemes are used for additional damping over oscillations. Thus, the interaction between multiple controllers of different damping schemes may cause an adverse effect on system damping over specific modes and destabilize the system if the coordination is inefficient [87]. Furthermore, damping by either PSS-based or FACTS-based system may not achieve fast and sufficient damping over the oscillations originating from complex power systems [88], [89]. These issues raise the requirement of the coordinated design of different damping controllers [90], [91]. Over the past years, many types of studies of the coordination of different controllers have been conducted. The coordination design for PSS and TCSC was presented in [92]. Furthermore, SVC was coordinated with PSS to enhance damping [93]. Other studies of the coordination of PSS-STATCOM and PSS-SSSC have been conducted in [94] and [95], respectively. Therefore, the basic purpose of coordination control schemes is the enhanced and robust damping over an oscillation, which is achieved using the simultaneous design of PSS and FACTS controllers.

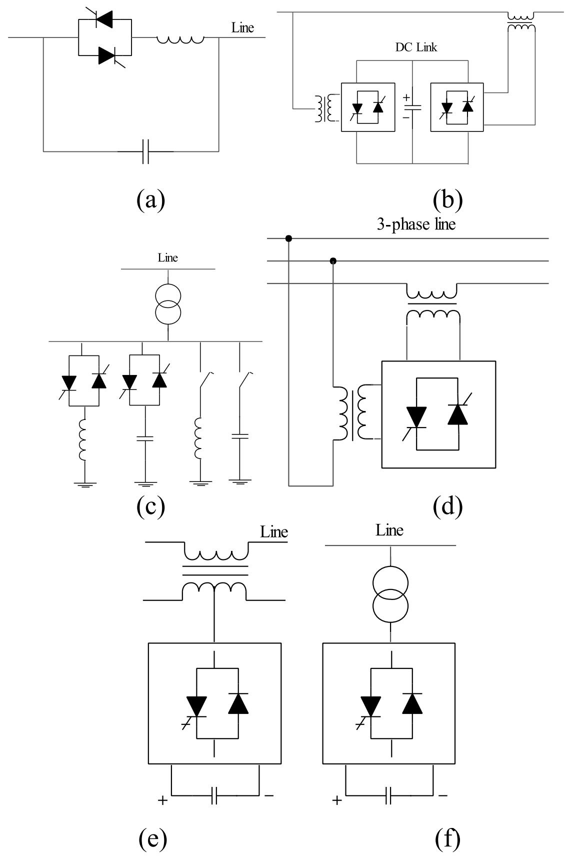

FIGURE 8. Functional diagrams of various FACTS devices: (A) TCSC, (B) UPFC, (C) SVC, (D) TCPST, (E) SSSC, and (F) STATCOM.

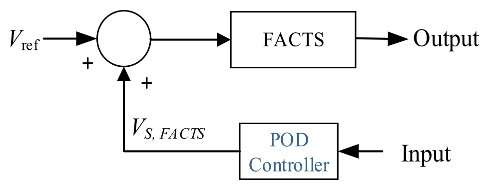

FIGURE 9. General diagram of FACTS device with corresponding POD controller.

D. 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], [96], and [97]. 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 [98], [99]. 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 [100]–[106]. 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 [106], [107].

The structures of the PSS controller and FACTS POD controller are similar to each other [108], [109]. These controllers are identical, as shown in Figs. 10 and 11.

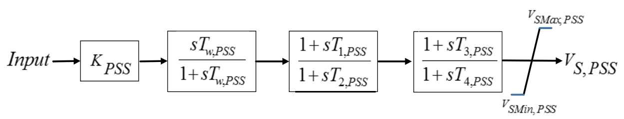

FIGURE 10. Lead–lag PSS controller.

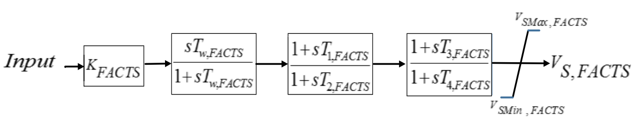

FIGURE 11. Lead–lag FACTS POD controller.

As shown in Figs. 10 and 11, the input is the appropriate input signal to the PSS and FACTS controllers. The rotor speed of the synchronous generator is the input signal commonly used for PSS [106], [110], [111]. By contrast, given that FACTS controllers are in the transmission system, the locally available signals are its preferred input. Local signals, such as the active power flow through FACTS devices and FACTS terminal voltage, are commonly used as the input signals for series-type and shunt-type FACTS controllers, respectively [107], [112], [113]. In this case, the exception approach has also been considered for the input signal selection of FACTS controllers. For instance, Abido and Abdel-Magid [114] used rotor speed as the input of FACTS controllers, which is unrealistic and should be avoided for such type of stability analysis.

As shown in Figs. 10 and 11, the time and gain constants K, T_1, T_2, T_3, and T_4 are the optimizing parameters usually considered the design challenge for damping controllers (for PSS and FACTS). By contrast, the time constant of washout block are insensitive and set in the range of 5–10 s [110]. Therefore, the total number of optimizing parameters in the two types of lead–lag controllers is five (excluding T_w). The optimizations of the parameters of the lead–lag controller are subjected to the boundary limits (minimum and maximum) according to Equation (14) as follows:

$$\begin{aligned} K_{\min} &\leq K \leq K_{\max} \\ T_{1,\min} &\leq T_1 \leq T_{1,\max} \\ T_{2,\min} &\leq T_2 \leq T_{2,\max} \\ T_{3,\min} &\leq T_3 \leq T_{3,\max} \\ T_{4,\min} &\leq T_4 \leq T_{4,\max} \end{aligned} \quad (14)$$

E. SYSTEM LINEARIZATION TECHNIQUE AND TOOLBOX

In particular, the design process of damping controllers is investigated under the power system stability study [115]. 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 [116]. The dynamics of a power system can be represented by a set of nonlinear ordinary differential equation (ODE) as follows:

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{f}(\mathbf{x}, \mathbf{u}) \\ \mathbf{y} &= \mathbf{g}(\mathbf{x}, \mathbf{u}), \end{aligned} \quad (15)$$

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:

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \mathbf{u} = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_p \end{bmatrix} \mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_q \end{bmatrix} \mathbf{f} = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix} \mathbf{g} = \begin{bmatrix} g_1 \\ g_2 \\ \vdots \\ g_q \end{bmatrix}.$$

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

$$\mathbf{x_0} = \mathbf{f}(\mathbf{x_0}, \mathbf{u_0}) = 0. \quad (16)$$

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

$$\dot{\mathbf{x}} = \dot{\mathbf{x}}_0 + \Delta\dot{\mathbf{x}} = f[(\mathbf{x_0} + \Delta\mathbf{x}), (\mathbf{u_0}, \Delta\mathbf{u})]. \quad (17)$$

If the nonlinear function $f(x, u)$ is expanded into Taylor's series around x_0 and u_0 while neglecting the higher terms, then the simplified expression for all $i = 1, \ldots, n$ can be expressed as follows:

$$\dot{x}_i = \dot{x}_{i0} + \Delta\dot{x}_i = f_i(x_0, u_0) + \frac{\partial f_i}{\partial x_1}\Delta x_1 + \cdots + \frac{\partial f_i}{\partial x_n}\Delta x_n + \frac{\partial f_i}{\partial u_1}\Delta u_1 + \cdots + \frac{\partial f_i}{\partial u_p}\Delta u_p. \quad (18)$$

By substituting $x_{i0} = f_i(x_0, u_0)$ into Equation (18), we obtain the following expression:

$$\Delta\dot{x}_i = \frac{\partial f_i}{\partial x_1}\Delta x_1 + \cdots + \frac{\partial f_i}{\partial x_n}\Delta x_n + \frac{\partial f_i}{\partial u_1}\Delta u_1 + \cdots + \frac{\partial f_i}{\partial u_p}\Delta u_p. \quad (19)$$

In a similar manner, the output equation can be simplified for all $j = 1, \ldots, q$, as follows:

$$\Delta y_j = \frac{\partial g_j}{\partial x_1}\Delta x_1 + \cdots + \frac{\partial g_j}{\partial x_n}\Delta x_n + \frac{\partial g_j}{\partial u_1}\Delta u_1 + \cdots + \frac{\partial g_j}{\partial u_p}\Delta u_p. \quad (20)$$

From Equations (19) and (20), the final linearized state space equations can be written as follows:

$$\begin{aligned} \dot{\mathbf{x}} &= A\mathbf{x} + B\mathbf{u} \\ \mathbf{y} &= \mathbf{x} + D\mathbf{u}, \end{aligned} \quad (21)$$

where A is the state matrix, B is the input matrix, C is the output matrix, and D is the feedforward matrix, which are presented as the following equations:

$$A = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \cdots & \cdots & \cdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix}, \quad B = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \cdots & \frac{\partial f_1}{\partial u_p} \\ \cdots & \cdots & \cdots \\ \frac{\partial f_n}{\partial u_1} & \cdots & \frac{\partial f_n}{\partial u_p} \end{bmatrix},$$

$$C = \begin{bmatrix} \frac{\partial g_1}{\partial x_1} & \cdots & \frac{\partial g_1}{\partial x_n} \\ \cdots & \cdots & \cdots \\ \frac{\partial g_q}{\partial x_1} & \cdots & \frac{\partial g_q}{\partial x_n} \end{bmatrix}, \quad D = \begin{bmatrix} \frac{\partial g_1}{\partial u_1} & \cdots & \frac{\partial g_1}{\partial u_n} \\ \cdots & \cdots & \cdots \\ \frac{\partial g_q}{\partial u_1} & \cdots & \frac{\partial g_q}{\partial u_p} \end{bmatrix}.$$

Thus, the final linearized equation (Equation (21)) 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 (21).

The modeling of the power system is inherent in proper and precise mathematical presentations [117]. 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 [105] and [116], 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 [115], [118], [119]. 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.

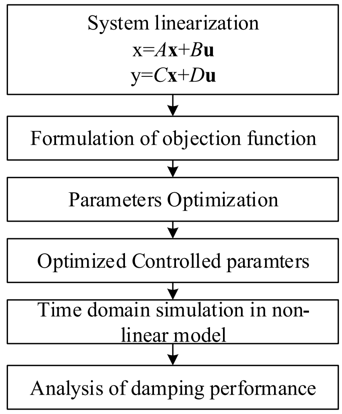

FIGURE 12. Major steps for controller design in linearized and nonlinear models of power systems.

In general, the design methodology of damping controllers involves two parts. In the first part, the controller parameters are optimized on the basis of a stability analysis of a linearized power system, as shown in Fig. 12. The analysis of system stability is conducted on the basis of eigenvalues obtained from the system state matrix [120]. In addition, the system stability is analyzed to formulate the objective function, and an optimization technique is applied to tune the parameters of damping controllers in the multi-machine system [110]. In the second part, the optimized parameters are used to run time-domain simulations to verify the system stability [111]. The time-domain simulations are analyzed to observe the damping improvement in terms of settling time and overshoot.

System stability is often determined on the basis of system analyses of either the linear model only [121] or the nonlinear model only [122]; nonetheless, the best practice is to include both analyses for a comprehensive view.

F. 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 ($\lambda_i = \sigma_i \pm j\omega_i$) obtained from state matrix (A) of the LTI state–space model. The eigenvalues of the state matrix (A) are derived as follows:

$$\lambda_i = eig(A) \quad (22)$$

where $i = 1, 2, 3, \ldots, n$. 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. The complex s-plane and stability criteria for system eigenvalues is shown in Fig. 13.

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).

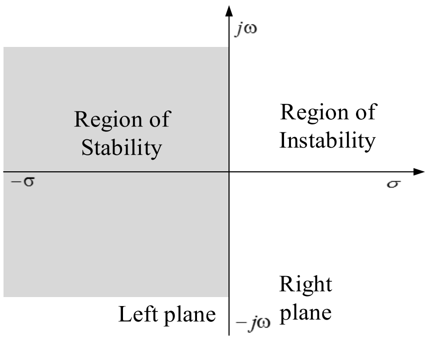

FIGURE 13. Complex *s*-plane and stability criteria for system eigenvalues.

The system is deemed unstable if any eigenvalue is on the right side of the *s*-plane. Therefore, all eigenvalues are required to move to the left side, and the shifting of eigenvalues is associated with the parameter optimization of the damping controllers. The techniques used to relocate the eigenvalues from the unstable region to the stable region include the formulation of the objective function and the application of the optimization algorithm. These techniques are discussed in the subsequent sections.

V. REVIEW OF THE OBJECTIVE FUNCTION FORMULATION

The application of the objective function with different formulations is proposed in designing a robust damping controller. Objective function formulation is sensitive to damping controller design. Thus, evaluating comparative performance under a common base is significant. The purpose of objective function formulation is to relocate eigenvalues efficiently from the unstable region to the stable region in the complex *s*-plane. In the past few years, many approaches have been adopted to formulate the objective functions in the damping controller design problem [123]–[125]. In general, objective functions are categorized into two types, namely, single- and multi-objective functions. In particular, objective functions are expressed in terms of the damping factors and damping ratios of eigenvalues and are determined from the real (σ_i) and imaginary (ω_i) parts of system eigenvalues as follows:

$$\text{Damping factor } \sigma_i = real(\lambda_i) \tag{23}$$

$$\text{Damping ratio } \zeta_i = -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \tag{24}$$

For an overview, the different formulations of the objective function are listed in Table 3. In the table, $i \in \{1, 2, 3, \ldots, n\}$ and $j \in \{1, 2, 3, \ldots, p\}$ are the system eigenvalues and operating conditions considered during optimization, respectively. Here, n is the total number of eigenvalues in the system and p is the total number of operating conditions considered during the design of the damping controllers. Furthermore, Fig. 14 shows the formulation of objective function on the basis of the damping factor and the damping ratio.

TABLE 3. Formulation approaches used for the objective function.

Formulation type	Formulation equation	Objective type
Single-objective function	$\max\{real(\lambda_{ij})\}$	Minimization
	$\min(\zeta_{ij})$	Maximization
	$\sum_{i=1}^{n}(1-\zeta_{ij})$	Minimization
Multi-objective function	$\sum_{j=1}^{np}\sum_{\sigma_{ij}\ge\sigma_0}(\sigma_0-\sigma_{ij})^2 + a\sum_{j=1}^{np}\sum_{\zeta_{ij}\le\zeta_0}(\zeta_0-\zeta_{ij})^2$	Minimization
	$-\max(\sigma_{ij}) + \min(\zeta_{ij})$	Maximization

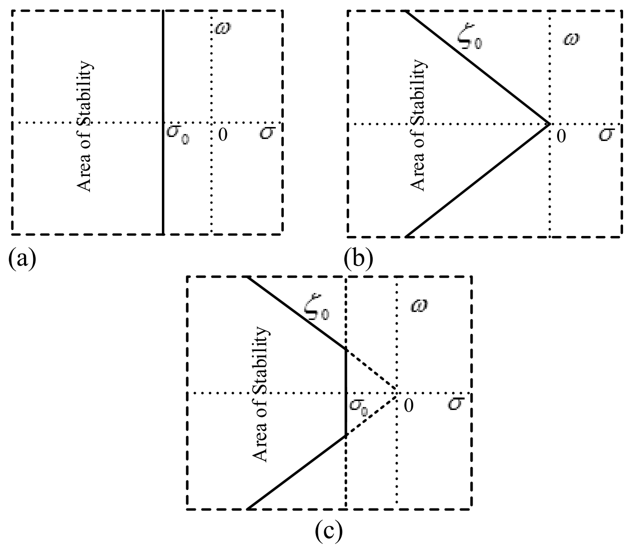

FIGURE 14. Objective function formulation approaches: (a) Damping-factor-based formulation, (b) damping-ratio-based formulation, and (c) D-shape-based formulation.

A. SINGLE-OBJECTIVE FUNCTION

The single-objective function has a mathematical expression that is associated with only one type of goal (objective) required to be achieved during optimization. The application of the single-objective function is presented in terms of either damping factors or damping ratios of electromechanical modes. In the literature, the worst damping factor (i.e., largest value) has been selected and then minimized through optimization [115], [126]–[130]. By contrast, the damping ratio is important in limiting the overshoot of oscillations, thereby ultimately improving the damping performance of controllers. Therefore, the lowest damping ratio has been determined and then maximized through the optimization of controller parameters [90], [124], [131]. However, system damping depends on the performance of the dominant electromechanical modes rather than of a single mode only. Thus, a single-objective function known as the comprehensive damping index, which includes dominant modes, has been proposed in [115] and [132]–[134].

B. MULTI-OBJECTIVE FUNCTION

The multi-objective function aims to achieve two or more objectives (or goals) in the formulation. In general, the improvement of the damping factor is associated with the improvement of the overshoot in oscillations. By contrast, the damping ratio enhances the settling time of oscillations. Therefore, the damping factor and damping ratio contribute to developing robust damping in the system performance. Usually, the damping factor and damping ratio are included in multi-objective functions.

In prior literature, the significance of multi-objective functions is realized in numerous studies of damping controller optimization [106], [110], [125]. In multi-objective techniques, the formulation needed to place eigenvalues in a D-shaped region is popular. Different approaches have been applied to form a D-shaped stability area. In [106] and [135]–[137], a technique to form a D-shaped stability zone was discussed; the technique is based on the expected damping factor and ratio for dominant modes. In such objective function, only the selected dominant modes are considered in the optimization. Another approach to set up the D-shaped region, which uses the algebraic sum of the worst damping factor and damping ratio, was presented in [125], [138], and [139].

VI. 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 [140], [141]. Optimization techniques may be categorized broadly into four, namely, (i) conventional, (ii) deterministic, (iii) heuristic, and (iv) hybrid techniques. The applications of these optimization techniques and their advantages and limitations are discussed in the subsequent sections.

A. CONVENTIONAL TECHNIQUES

In the frequency domain, the optimizations of the controller parameters are conducted on the basis of the classical control theory concept. This type of technique includes bode plots, root locus, and phase and gain margin methods. In the past decades, many applications of classical optimization techniques have been reported for tuning the damping controller [142], [143]. The damping controller optimized by the classical methods usually creates a problem in which the control should be readjusted when the system condition is changed. Otherwise, the control scheme may no longer effectively work to satisfy the specification. To avoid this issue, modern control theory-based techniques, such as H_∞ [144], [145] and μ synthesis optimization [146], were used to design the damping schemes. However, many difficulties related to the H_∞ and μ synthesis optimization techniques were reported in [147]. For example, the difficulties in the selection of the weighting function, the requirement of system model order reduction for practical application, and the pole–zero cancellation phenomenon reduce applicability because of the requirement of a special format for uncertainties. Thus, other optimization techniques are needed for the design of damping controllers.

B. DETERMINISTIC TECHNIQUES

Deterministic techniques involve mathematical programming that predicts future behavior precisely from the past behavior of a set of data. Deterministic techniques take advantage of the analytical properties of the problem to converge to a global optimum solution. Deterministic techniques, such as linear programming, have been applied to PSS optimization [148]. Gradient-based sequential quadratic programming (SQP) was used to achieve optimum damping performance [133]. However, deterministic techniques are crucial to selecting the initial point. Moreover, achieving the optimum solution is difficult. In the case of a large number of parameter optimizations for a large power system, solution convergence seems nearly impossible. Thus, the use of deterministic techniques is limited to this type of design application. In this case, other optimization techniques, such as heuristic algorithms, are preferred as the efficient alternative to deterministic techniques.

C. 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 metaheuristic 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.

1) TABU SEARCH

Tabu search (TS) is a metaheuristic algorithm that uses local search methods with adaptive memory-based techniques. TS facilitates flexible search experiences in constraint-based optimization problems. An advantage of TS is that the optimization does not require an initial guess of the solution. Abido illustrated the application of TS for conventional PSS tuning on the basis of the single-objective function [149]. Robust design of PSS with different operating conditions has been illustrated using TS [150]. In these studies, the formulation of the objective function was simple and based on the single-objective function. Another study using TS was described in the case of complex multi-objective function for improved damping performance [151]. TS for optimizing series FACTS-based SSSC controller has been considered to improve damping over inter-area modes of oscillation [152]. In a practical scenario, robust damping is only achieved when all parameters are tuned precisely. In this case, the numbers of optimized parameters are quite immense for interconnected power systems. In addition, the global search efficiency of TS is relatively poor compared with other algorithms; hence, TS has not been recommended in subsequent research [153].

2) SIMULATED ANNEALING

The constraints of the optimization problem are an obstacle in determining the optimum solution of damping controller design in the multi-machine power system. Simulated annealing (SA) easily overcomes this limitation by incorporating the problem constraints during optimization [154]. The initial guess of the optimal solution is also no longer required for SA. In addition, the structure of SA is simple and easy to implement. These advantages encouraged researchers to select SA for optimum damping controller design in interconnected power systems [155]. However, most of the studies used the single-objective function and regarded SMIB as the test system for their studies. Moreover, the design parameters were associated with K, T_1, and T_3, and other parameters (T_2 and T_4) were ignored during optimization. Research has also shown some limitations of SA for practical application [156] and recommended that future research avoided using SA.

3) GENETIC ALGORITHM

Genetic algorithm (GA) was proposed for the simultaneous design of multi-machine PSS in [114]. GA was recommended to formulate the multi-objective function for robust damping performance [112]. Another research was conducted using GA to design the coordination control of PSS and TCSC [157]. However, researchers have discovered some deficiencies of GA, such as premature convergence caused by the local minimum stagnation problem. Various modifications have been proposed by many authors to overcome the limitations of GA [158]. 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 [159]. Real-coded GA has also been presented for the analysis and design of the SSSC-based damping controller [160]. 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 [124]. The effectiveness of GA is affected by the choice of the range of search space. Differential evolutionary algorithm (DEA) was introduced for robust damping in a multi-machine system that incorporates the concept of a moving search space instead of a fixed search space [125].

4) BACTERIAL FORAGING OPTIMIZATION ALGORITHM

Bacterial foraging optimization algorithm (BFOA) was developed according to the foraging social behavior of *Escherichia coli* bacteria [161]. The basic steps of BFOA are chemotaxis, swarming, reproduction, elimination, and dispersal. Comparative analyses have shown that BFOA performs better than GA [162]. Several applications of BFOA have been reported for tuning the controller of various damping schemes of PSS, SVC, and TCSC [163]. However, the presented approaches avert many parameters to clarify optimization complexity. In addition, BFOA shows insufficient convergence for large constrained problems. To deal with this problem, several hybrids and enhanced versions of BFOAs were presented in other studies [164].

5) 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 [134], [165], [107]. 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 [166]. Modification of PSO has been proposed to improve the damping performance in the power system [115].

6) CHAOTIC OPTIMIZATION ALGORITHM

The application of stochastic chaotic optimization algorithm (COA) has been described for PSS optimization using a multi-objective D-shaped function [107]. The presented COA showed improved solution convergence and high precision results, although the study used a three-machine nine-bus power system to conduct the analyses. However, the robustness of COA may significantly vary with the increase in problem dimension and thus may adversely affect performance in the case of a large test power system. In this regard, a study was conducted to optimize the coordination control of PSS and SSSC by modifying COA for a high-dimensional problem with a large search space [105]. This study proposed individual strategies for global and local search using the improved logic map-based COA (ILCOA). However, in this research, the consistency of solutions obtained using ILCOA was not validated through statistical analyses.

7) IMMUNE ALGORITHM

Immune algorithm (IA) is another nature-inspired algorithm; it is based on the principle and processes of the vertebrate immune system. Different versions of IA have been applied in many types of research involved in the optimization of various types of damping controllers [167]. IA performs better in the exploration strategy than in the exploitation strategy in finding a possible solution for the optimum parameters of the damping controller. The modified version of IA was presented in [168] to improve the exploitation process using the local search strategies. Another concept that includes the reduction of search space gradually to discover additional in-depth information for enhanced search exploitation was introduced by proposing the RIAPM (SA) [159]. The optimum solution can only be achieved when the search exploration and exploitation strategies are balanced. Moreover, the proposed RIAPM techniques can become trapped in the local minimum traps because of the reduction of the search space and the absence of balanced search control strategies.

8) GRAVITATIONAL SEARCH ALGORITHM

The law of Newtonian gravity and mass interaction was mimicked to develop the gravitational search algorithm (GSA) [169]. Eslami presented the GSA for the coordination control of TCSC and PSS [170]. However, the application of GSA in previous publications has been relatively rare compared with that of other heuristic algorithms. The reason can be its limitations for robust performance in multimodal search optimization [171].

9) POPULATION-BASED INCREMENTAL LEARNING ALGORITHM

Population-based incremental learning (PBIL) is an optimization technique that combines some features of GA with competitive learning on the basis of ANN. PBIL has no crossover operator, unlike GA [103]. Therefore, PBIL is easy to implement and robust in terms of problem representation. Multi-machine PSSs have been optimized with the use of the PBIL algorithm for better performance compared with GA-based design over different system uncertainties [172]. However, performance analysis in a large power system along with solution consistency based on statistical view were absent in the proposed research. In addition, the deficiencies of GA may also limit the attainment of robust damping using the PBIL algorithm.

10) DIFFERENTIAL EVOLUTIONARY ALGORITHM

The DEA is another population-based global optimization technique and somewhat considered the improved version of GA. Similar to other heuristic algorithms, the DEA is also capable of solving problems in complex problem domains with non-differentiable, nonlinear, and multimodal optimization [173]. The DEA was proposed for the optimal tuning of TCSC- and SSSC-based controllers [174]. Another coordinated control design between PSS- and SSSC-based controllers was illustrated in [102]. The DEA was proposed for the simultaneous and coordination control of PSS- and TCSC-based POD controller optimization [175], [176]. Although the DEA has been applied in many types of research, the selection of control parameters for the DEA is a difficult task. In addition, the DEA has many limitations, such as slow convergence, poor solution quality, and premature stagnation [177]. These reasons do not encourage recommending DEA in further research on damping controller optimization.

11) OTHER ALGORITHMS

Evolutionary programming (EP) has been applied for PSS optimization design [178]. The coordination design of PSS- and STATCOM-based stabilizers have been proposed simultaneously using the seeker optimization algorithm [94]. Cultural algorithm (CA) and firefly algorithm (FA) were reported for the optimal design of multi-machine PSS separately in [110] and [179], respectively. However, CA is considered the improved version of GA. Therefore, CA may have some deficiencies that are similar to those of GA. FA has some limitations, and the required modification was proposed in [180]. The nature-inspired BAT algorithm was developed according to the echolocation behavior of microbats. Two different types of research have individually presented the BAT algorithm for PSS optimization in the multi-machine system [106], [111]. Currently, the extensive application of various heuristic algorithms for damping controller optimization is noticeable. For a quick overview, Table 4 summarizes the advantages and drawbacks of popular heuristic algorithms.

12) HYBRID ALGORITHMS

Different techniques have been proposed for the optimization of damping controllers. The main goal behind the use of various techniques is to achieve robust damping over power system oscillation. Although different techniques have some advantages and disadvantages over one another, attempts to achieve improved performance continued through the use of hybrid techniques. Many hybrid techniques have been reported to obtain improved robust performances over the years. The hybrid BF-PSO technique was developed by combining the BFOA and PSO techniques. BF-PSO was successfully applied for PSS optimization and coordination damping of PSS and SVC controller optimization [162], [91]. Chaotic ant swarm optimization (CASO), which combines ACO with chaotic foraging behavior, was proposed in [97] to overcome the premature convergence caused by local minimum traps. The culture–PSO–co-evolutionary algorithm combines the CA, PSO, and co-evolutionary algorithms [109].

Recently, another hybrid algorithm was proposed for enhanced damping on the basis of global and local search concepts [175]. The combination of global and local search strategies is required for efficient search performance in the multimodal optimization problem. In this regard, a hybrid technique h-FAPS that combines FA with pattern search (PS) technique was proposed for SSSC-based controller design in [181]. In this work, h-FAPS takes advantage of FA's global search strategy and PS's local search strategy. Three control parameters of FA can significantly influence the optimization results if they are not properly selected. Mixed integer

TABLE 4. Major advantages and disadvantages of popular heuristic algorithms.

Heuristic algorithms	Major advantages	Major disadvantages
GA [114]	▪ Easy to learn and implement ▪ Does not require knowledge of mathematics	▪ No assurance of an optimum solution ▪ Incapability of solving various types of complex optimization problems ▪ The tendency to converge in the local optima
TS [153]	▪ Escapes from local minima as well using the "tabu list"	▪ Slow convergence rate ▪ The poor solution for the high-dimensional problem
SA [155]	▪ Can provide a solution even in a large search space ▪ Easy to learn and implement ▪ Provides relatively good solutions for specific optimization problems	▪ Slow convergence rate ▪ Incapability of solving complex multimodal problems ▪ Performance deterioration in large dimension problems
DEA [173]	▪ Can solve multidimensional, non-differential, non-continuous	▪ The difficulty of selecting the control parameters ▪ No assurance of solution precision
PSO [166]	▪ Converges quickly ▪ Can solve complex optimization problems in different application domains	▪ The negative effect on solutions due to improper selection of control parameters ▪ The tendency of being trapped in local minima ▪ Poor performance in high-dimensional and multimodal optimization
IA [167]	▪ Performs search exploration process well	▪ Poor search exploitation

ant direction hybrid DE was proposed for PSS parameter tuning in [182]. Heuristic algorithms, such as artificial bee colony (ABC), have been combined with the deterministic technique SQP to establish the hybrid ABC-SQP for optimum damping performance [183]. The hybrid TS-EP technique was also applied for PSS optimization [184]. The combination of algorithms may achieve some success in overcoming some limitations. However, the overall computational burden and complexity increase.

VII. LIMITATIONS OF EXISTING APPROACHES FOR CONTROLLER DESIGN

To date, many types of research have presented the efficiency of damping controller design by incorporating different formulations of the objective function and optimization techniques. Nonetheless, some limitations are necessarily noticeable in the approaches during the design procedure. The solution convergence of heuristic algorithms is an important characteristic that justifies their efficiency. Many authors have compared their proposed algorithms with other heuristic algorithms through single-convergence curves [106], [110]. They concluded that the proposed algorithms are fast and good for efficient solution convergence. The path of solution convergence changes every time because heuristic algorithms use stochastic methods (randomization techniques). Therefore, this type of comparison is insufficient for the justification of solution convergence. The comparison can be extended to measure the consistency of solution convergence. In this case, statistical analysis can be incorporated with this type of measurement.

The performance of heuristic algorithms is problem-oriented. The increase in problem complexities may prevent the algorithms from obtaining the required optimized parameters. The problem dimensions of optimization problems play an important role in the performance of heuristic algorithms. Many authors have considered SMIB and small-sized test power system, such as a three-machine nine-bus system [106], [165]. Their analyses yielded insufficient information about how the design performance of their proposed algorithms varies with the increase in problem dimension (for large power systems).

Robust and efficient damping performance is ensured only when all the parameters (K, T_1, T_2, T_3, and T_4) of the damping controllers are optimized properly. Numerous studies ignored the parameters T_2 and T_4 of damping controllers to reduce design complexities [106], [125], [165]. This type of consideration is a clear indication of the lack of proper comprehensive analysis during the design of damping controllers.

VIII. CURRENT ISSUES AND CHALLENGES

To date, many types of research have been presented for the efficiency of damping controller design by incorporating different formulations of the objective function and optimization techniques. Some challenges have been observed in the design procedures of these approaches.

A. OBJECTIVE FUNCTION

Over the past years, various studies of controller design have been conducted [111], [124], [125], [133], [185]. In these studies, the authors considered different approaches to formulate the objective function. The objective function is an important part of controller design; thus, its inappropriate formulation may significantly contribute to achieving poor and insufficient damping by the damping schemes. Therefore, the objective function is a foremost part of the robust design of damping controllers. No research has compared the performances of different formulations of the objective function. Prior to this issue, determining the best approach to formulating an objective function for rigorous design is necessary to maximize the stability of the multi-machine power system.

B. DAMPING CONTROLLER DESIGN AND PERFORMANCES

Designing a damping controller efficiently is another challenge for the optimal performance of the multi-machine power system. The design of damping controllers is the primary step undertaken to ensure the stability of the multi-machine power system. The design of damping controllers in the large power system is a multimodal optimization problem, which is complex and difficult to solve. In this case, traditional algorithms do not perform well because their performance deteriorates with increased problem dimension. In addition, the tendency to become trapped in the local minima is the most common pitfall of traditional heuristic algorithms [160]. In such cases, the optimum solutions are not easily obtained, consequently preventing the achievement of robust damping by the damping schemes.

C. CONVERGENCE RATE

Building a new and efficient alternative to the single-convergence curve to measure the convergence rate of the optimization technique is a challenging task. The solution convergence of heuristic algorithms is an important characteristic that justifies their efficiency. Many authors have compared their proposed algorithms with other heuristic algorithms through single-convergence curves [106], [110], [124]. They concluded that the proposed algorithms are fast and good for efficient solution convergence. Heuristic algorithms use stochastic methods (randomization techniques); thus, the path of solution convergence changes every time. This type of comparison is insufficient for the justification of solution convergence. The comparison can be extended to measure the consistency of solution convergence. In this case, statistical analysis can be incorporated with this type of measurement.

D. OPTIMAL DAMPING CONTROLLER IN LARGE POWER SYSTEMS

The appropriate selection of controller parameters is another challenge in achieving the optimal solution [47], [111]. In the case of the multi-machine power system, the numbers of optimizing parameters for damping controllers are relatively large and the complexity of the optimization problem increases significantly. Given that most of the optimization techniques show poor solution and consistency for a large number of parameter optimizations, the development of controller design is required to improve the damping performance and ensure stability even for a large power system. Robust and efficient damping performance is ensured only when all the parameters (K, T_1, T_2, T_3, and T_4) of damping controllers are optimized properly. Numerous studies ignored the parameters T_2 and T_4 of the damping controllers to reduce design complexities [106], [125]. This type of consideration clearly indicates a lack of proper comprehensive analysis during the design of damping controllers.

Damping controllers are optimized in a linearized model of the power system. In the linearized method, the optimization of damping controllers is time consuming. Therefore, this method does not have the live tuning facility of damping controllers. The time of optimization also increases with the increase in power system size. Therefore, the optimization of damping controllers is not easily obtained in the case of large power systems.

E. IMPLEMENTATION OF THE HEURISTIC ALGORITHM

The application of heuristic algorithms is the most common and widely accepted optimization technique for the design of damping controllers [125], [160]. Many types of research using various traditional heuristic algorithms have been reported. In general, the performance of heuristic algorithms is a problem-oriented application. Many applications of heuristic algorithms have been presented in SMIB and small-sized multi-machine systems to investigate the damping performance [186], [187]. However, investigating the variation of design performance with the increase in problem IPFC (large power system) is important. In several cases, the authors considered a reduced number of controllers and optimizing parameters to avoid the design complexities [125]. Their analyses have insufficient information about how the design performance of their proposed algorithms varies with the increase in problem dimension (for large power systems).

IX. 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. In addition, various optimization techniques generally applied for controller parameter optimization are categorized and discussed in terms of their advantages and limitations. Finally, the major limitations of the 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.

- The solution convergence of heuristic algorithms can be statistically analyzed and applied to the optimized damping controller for the justification of efficient solution convergence.
- Proper comprehensive analysis with sufficient information of all optimizing parameters of the damping controllers can ensure robust and efficient damping performance.
- The appropriate formulation of the objective function in designing a robust damping controller can significantly contribute to maximizing the stability of the multi-machine power system.
- An advanced optimization algorithm needs to be implemented in designing an intelligent controller for the PSS and multi-FACTS controller to ensure composite enhanced performance.

Thus, in this study, the damping schemes and controllers, ultimate challenges and issues, and recommendations regarding the development of optimized damping controllers are discussed, and recommendations for future research and development of an advanced damping controller for the multi-machine power system are provided. This study also highlighted some further investigations for future works such as (i) advanced optimization algorithms are suggested to be implemented with intelligent controllers such as fuzzy logic, neural network, and PID for PSS and FACTS control, (ii) the identification of optimal location of FACTS devices needs to be explored, (iii) the coordination design of PSS and multiple FACTS (such as SVC, TCSC, SSSC, UPFC etc.) controllers need to be implemented to provide composite enhanced performance and (iv) the damping controller design for relatively large power system (more than 5-area system) such as IEEE 300 bus system needs to be studied.

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