ARQII Publication
APPLICATIONS OF
MODELLING AND SIMULATION
http://arqiipubl.com/ams eISSN 2600-8084 VOL 6, 2022, 134-149

Mitigation of Power System Oscillation in a DFIG-Wind Integrated Grid: A Review

Theophilus Ebuka Odoh[1*], Aliyu Sabo[2] and Noor Izzri Abdul Wahab[2]

[1]Center for Power System Dynamic Simulation, Department of Electrical and Electronic Engineering, Faculty of Engineering and Technology, Nigeria Defence Academy Kaduna, Nigeria
[2]Advanced Lightning, Power and Energy Research (ALPER), Department of Electrical and Electronics Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

*Corresponding author: theophilusodh@gmail.com

Submitted 14 October 2022, Revised 10 November 2022, Accepted 30 November 2022, Available online 13 December 2022.

Abstract: The continuous rise in demand for power supply has made researchers and power system engineers seek alternatives through renewable energy sources to complement the power supply in the power system grid. Wind energy conversion system (WECS) which is the means of harnessing power generation through wind is reportedly one of the most widely installed renewable alternative sources globally. Integrating WECS into the conventional power system grid results in a complex power system grid. Thus, during a disturbance or a fault period on the grid, if proper control measures are not put in place, power system instability due to power system oscillations arises. One such control measure is the damping controller which is coupled to the generating plant through its excitation system. Damping controllers help to dampen power system oscillations, but due to the dynamic nature of the power system and uncertainties inherent in a wind-integrated power grid system, fixed damping controller parameters cannot effectively dampen power system oscillations. Hence, damping controller design becomes an optimization problem. This research reviews damping controller design in a wind-integrated system using optimization techniques.

Keywords: Artificial intelligence; Damping controller; Optimization; Review; Wind energy conversion system.

1. INTRODUCTION

Recent power system grids are massively interconnected with newer technologies. Control devices are also integrated into the system, for efficiency enhancement and economic benefits. Thus, Sabo and Wahab [1] concludes that the power system grid is the biggest artificial living network on earth. Integration of large renewable energy resources like wind energy into the existing power system grid has increased significantly in the last decade due to the increasing demand for power supply, therefore, improving power supply and reducing greenhouse gas emissions [2]. Wind energy is one of the most widely utilized renewable alternatives at present. Even with the global health challenge which resulted in cancelled installations, according to [3] in 2020, global wind energy installation was estimated at 93 GW. Thus, making the total estimated global wind energy capacity near 743 GW with most installations onshore [3].

Wind energy conversion systems (WECS) in form of wind turbines are the term for wind renewable energy and it has various designs and control methods. Compared with conventional generation, WECS is equipped with power electronics converters, which enables its characteristic of faster response and better control [4]. Integration of WECS into the grid has various challenges, the generation uncertainty, power quality (PQ) issues, and power system stability [2]. Power system stability has been recognized as an important problem for secure system operation [5]. The capacity of an electric power system to regain operational equilibrium following a physical disturbance is known as power system stability [5]. The significance of this phenomenon has been demonstrated by various major blackouts due to the instability of the power system [5]. The most crucial factor in achieving safe and dependable operation is power system stability. Electricity is in great demand dramatically as a result of advances and complexities in technology. This persistent demand leads to integrated power systems through transmission lines, to meet the increasing demand. Also, the existing power grid system operates at its maximum capacity, hence any disturbance or fault on the power system grid may lead to oscillations in the power system grid. Therefore, solving the power system oscillation problem is a global concern.

The generator excitation system began using fast-acting, high-gain automated voltage regulators (AVR) in the early 1960s, which further opened the door to the issue of oscillations in form of low-frequency electromechanical oscillations (EMOs) in the power system by lowering the damping torque. To minimize the low-frequency oscillations, coordination is adopted between a damping controller and the AVR of the excitation control system to mitigate these low-frequency oscillations and improve the stability of the power system. In addition to the AVR signal, damping controllers inject a signal into the excitation system to increase the machine damping torque. Low-frequency oscillations in the system are dampened as a result of this phenomenon. Damping controllers increase the level of angle stability, and transmission line power-carrying capability [6, 7]. The rotor speed, frequency, or power are the inputs to the damping controller.

The selection and proper tuning of the damping and AVR controller parameters determine how well the power system oscillations will be damped. There are various types and schemes for designing damping controllers such as PSS type, FACTS type and a combination of PSS and FACTS types known as coordination damping control. Recently with the evolution of machine learning (ML) and the continuous penetration of renewable energy sources (RESs) like the wind to the electric power grid, ML damping controller systems have been proposed by [8-11]. The non-linear nature of the power system and the uncertain wind power generation limits the efficiency of a damping controller with fixed parameters in damping power system oscillations [12]. For effective damping operation, the design problem of damping controllers is converted to an optimization problem. According to the "No Free Lunch Theorem", no algorithm can outperform the others in all possible optimization problems on average [13]. One algorithm may perform better for some optimization problems, but it may perform worse for other types of optimization problems. No review has discussed emerging damping controller design schemes and their performance in a wind energy-integrated system prior to this review. Therefore, the contributions of this study include:

a) Emerging damping controller designs like ML and performance evaluation in a wind energy integrated system.
b) Review of integral time error based, and eigen-value based analysis in accessing power system stability.

2. METHODOLOGY

The focus of this review is on the optimal design of a damping controller in a doubly fed induction generator (DFIG) wind integrated power grid system by exploring various techniques of optimization. High-quality impact factor literature was employed to achieve this goal. This high impact factor literature was chosen by evaluating its title, followed by the abstract, the paper content, and finally results. Citations and the process of review were also considered. Therefore, published literatures from 2016 were selected.

The results from this review process are divided into seven parts. First, an overview of developments in WECSs especially doubly fed induction generator (DFIG) wind systems. Secondly, WECS integration into the power grid system is discussed. Thirdly, power system oscillations including dynamics of the rotor. Fourthly, damping controllers are highlighted including PSS, FACTS, coordinated design, and ML. Next, system linearization technique, eigenvalues, integral time error-based function, and time domain simulation in a non-linear model are discussed. Then, formulation of the objective function is discussed including singular and multiple-objective functions. Finally, different optimization techniques for designing a damping controller are presented. The review concludes with suggestions and recommendations for future development on oscillation damping in a DFIG wind-integrated power grid system.

3. WIND ENERGY CONVERSION SYSTEM

Wind energy is among the fastest-growing renewable energy resources [14]. Wind energy has long been regarded as one of the most potent sustainable energy sources capable of ensuring alternative energy security. An impressive rise in the use of wind turbine systems has increased research and development in many areas [15]. One of the fastest-growing and most advanced renewable sources across the globe is wind energy [16]. Though wind energy depends heavily on weather conditions, wind speed, and topology, these conditions make wind energy very unpredictable, and thus wind turbine's energy generation may not be as consistent as that from conventional sources. This leads to integration into the grid to supplement the available power supply. This grid integration affects the stability of the power system [16-18].

There is existent of wind almost throughout the earth, and wind energy is produced by exploring the power resulting from kinetic energy in a blowing wind thus is referred to as wind power. Wind power is at present a very advanced technology employed commercially in electricity generation since its first usage in the 1990s. Wind power technology is on the increase mostly in countries where a majority of its electricity generation is from fossil fuels. Wind power has the advantage of wide practical applications also in remote areas in form of wind farms. However, for flexibility, sustainability, and maximum stability, it should be connected to the power grid system. Wind farms can be categorized depending on their location either land which is called onshore wind farm or on the sea known as offshore wind farm. Onshore wind farms are normally located close to power grid stations on mountains or near coastal areas, while offshore wind farms are located in the ocean deep. In recent years offshore wind farms are slowly increasing in global installed capacity owing to the uniform wind speeds available in the ocean deep [19]. As oceans cover more than 70% of the earth's surface and wind energy above seas can also be absorbed to generate large amounts of electricity, integration of offshore wind farms can be accounted for as a benefit of renewable energies of ocean and wind [20]. A record global wind energy capacity of about 93 GW was installed across the globe, with the onshore wind system accounting for the majority at 86.9 GW and offshore with around 6.1 GW. The cumulative wind power capacity installed globally by end of 2020 in estimate was around 743 GW [3]. Figure 1 shows the global wind installed capacity and annual additions from 2010 to 2020.

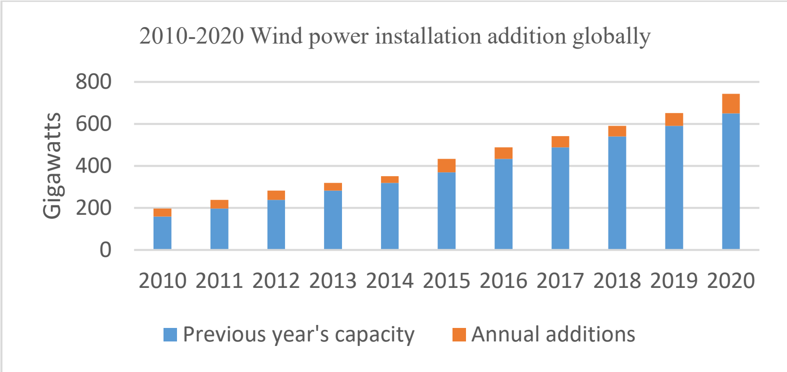

Figure 1. Wind power global capacity and annual additions [3]

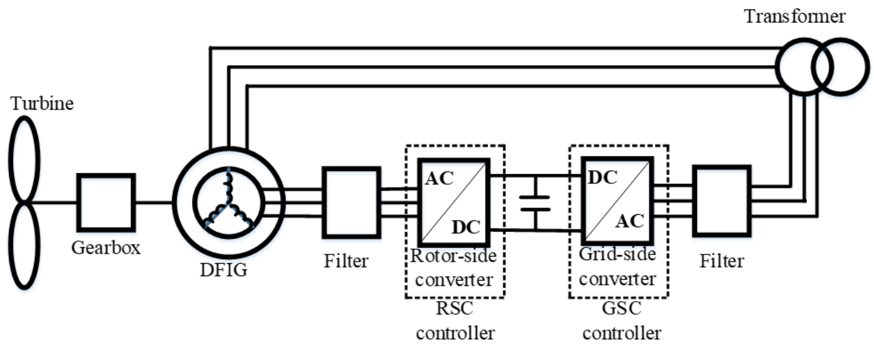

Figure 2. DFIG wind energy conversion system [24]

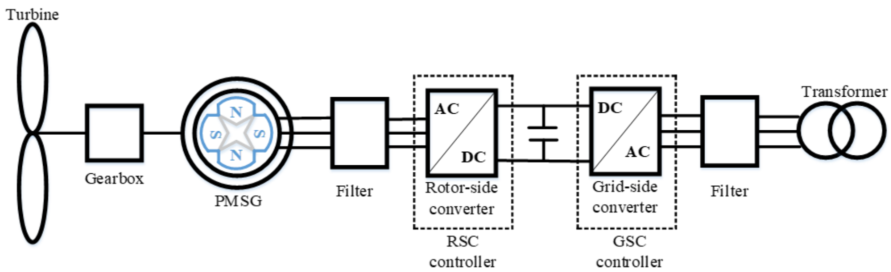

Figure 3. Wind energy conversion system using PMSG [24]

In WECS, generators that are often utilized for wind power generation include electrically excited synchronous generators (EESG), squirrel-cage induction generators (SCIG), PMSG and DFIG) [21]. The two widely utilized are PMSG and DFIG. Their main features include fast control ability and high efficiency in energy conversion. In terms of market shares in wind power generation, PSMG and DFIG WECSs are almost the same [22]. For example, a wind turbine is attached to the DFIG system through a gearbox to transform mechanical power from wind to electrical power.

The typical wind turbine system has a gearbox that contains two helical gear stages and one planetary gear stage. The low-speed shaft from the wind turbine rotor is connected to the planetary stage, while the high-speed shaft from the generator is connected to the final helical stage [23]. A three-phase winding rotor used by DFIG allows for a wide range of variable speeds. It is controlled by changing the converter's rotor current flow of both active and reactive powers [21]. One disadvantage of the DFIG system is that it requires constant maintenance of the gearbox and brushes to reduce mechanical failure possibility. Figure 2 shows a DFIG WECS.

In place of coils, PMSG uses permanent magnets to provide an excitation field and requires less maintenance because of its few moving parts. Additionally, even though it has a high capital cost, power converters in PMSG help in variable wind speed generation owing to their high efficiency in wind energy conversion and long lifespan [24]. Traditional synchronous generators (SG) are connected directly to the grid, but PMSG requires controllers and converters to optimize wind energy generation and grid integration. Thus, a rotor-side converter and a grid-side converter, known as a frequency converter, are connected through a filter to the PMSG before transmitting the power generated to the grid. The grid side converter helps to control the DC (direct current) link voltage by transporting active power generated to the power system grid network through the pulse width modulation voltage source converter. At the same time, the rotor side converter controls the PMSG operation through a rectifier or a pulse width modulation voltage source converter. Figure 3 shows a WECS using a PMSG.

Traditionally WECSs in form of wind farms are located onshore as a result of ease in construction, maintenance, energy transmission, and lower costs as regards to offshore wind farms [25]. These days interest in offshore wind farms is tremendously increasing across the world. This is because of strong and steady sea wind and reduced visual and acoustic impact on humans [26]. As the large amount of land engulfed in citing onshore wind farms, offshore wind farm development has been invested in lately [25]. Presently Europe is the leader in offshore wind power plant development, as at 2018 total global installed offshore wind capacity was 22,045 MW with about 80% concentrated in Europe [27]. To interconnect offshore wind farms to offshore substations, a medium voltage AC network is used and to transmit the power generated from offshore substations to power grid systems onshore, a copper conductor high voltage dc or high voltage AC transmission line is used [28]. The onshore grid substations normally operate at low frequency and medium voltage which translates to high voltage transformers and costly structures.

A proposed isolated AC-DC interfaced converter for medium voltage direct current was used to replace an existing AC system in [25]. This amounts to cost reduction and power density increase in offshore systems. It is noted that DC superconducting high-temperature cable can transfer more power at approximately three times than its AC counterpart of the same size [29]. This can be attributed to various features of DC operation, which include higher dielectric material and DC, electrical breakdown strength increase almost double that of AC cable, DC superconducting cable electrical resistance is about 100 times lower than the traditional DC cable leading to a very low electrical loss in a DC superconducting cable [29].

3.1 Single Machine Infinite Bus (SMIB)

The most commonly used terminal constraint for a single machine is the popular infinite bus. In most power engineering terminology, an infinite bus is a bus with fixed voltage (both magnitude and angle) and also frequency. The infinite bus test system can be used to represent a strong grid connection, where injected power will be absorbed at the connection point of the infinite bus without a considerable change in frequency or system voltage [30].

As seen in Figure 4, the SMIB test system consists of one synchronous generator hence the name single machine. The synchronous generator or machine consists of a stator with armature windings and a rotor (cylindrical rotor or salient pole) with field windings. The stator and rotor are separated by a small air gap [30]. As regards the rotor shape and air gap, there exist two axes of symmetry d-axis and the q-axis, as rotor rotates relative to the stator, self and mutual inductances are induced by time-varying fluxes between the armature and rotor circuits. In synchronous machine modeling, the time-varying inductances complicate the model but dq transformations are used to simplify the model [31]. The synchronous machine is modeled using Differential Algebraic Equations (DAEs).

The power system dynamic modeling is done using differential algebraic equations, for *n* number of machines representing the grid synchronous machine, and its voltage regulator known as automatic voltage regulator modeled as:

$$T'_{d0i}\frac{dE'_{qi}}{dt} = -E'_{qi} - (X_{di} - X'_{di})I_{di} + E_{fdi} \tag{1}$$

$$T'_{q0i}\frac{dE'_{di}}{dt} = -E'_{di} - \left(X_{qi} - X'_{qi}\right) \tag{2}$$

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s \tag{3}$$

$$\frac{2H_i}{\omega_s}\frac{d\omega_i}{dt} = T_{Mi} - E'_{di}I_{di} - E'_{qi}I_{qi} - (X_{di} - X'_{di})I_{di}I_{qi} - \mathrm{D_i}(\omega_i - \omega_s) \tag{4}$$

$$T_{Ai}\frac{dE_{fdi}}{dt} = -K_{Ai}E_{fdi} + K_{Ai}\left(V_{refi} - V_i\right) \tag{5}$$

$$T_{Ei} = E'_{di}I_{di} + E'_{di}I_{di} + \left(X'_{qi} - X'_{di}\right)I_{di}I_{qi} \tag{6}$$

All the symbols are defined in Table 1 [32]. From Equation (4) electrical torque is employed. Algebraic equations of one stator's synchronous machine are represented as:

$$\begin{aligned} V_{di} &= -R_{si}I_{di} + X'_{qi}I_{di} + E'_{di} \\ V_{qi} &= -R_{si}I_{qi} - X'_{di}I_{di} + E'_{qi} \end{aligned} \tag{7}$$

Algebraic equations of all stators in the synchronous machines of a power system are converted into matrix form as:

$$\begin{aligned} V_d &= -R_sI_d + X'_qI_q + E'_d \\ V_q &= -X'_dI_d - R_sI_q + E'_q \end{aligned} \tag{8}$$

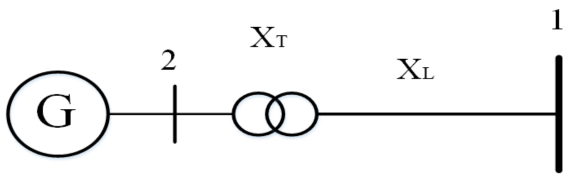

Figure 4. SMIB power system [32]

Table 1. Symbols and definitions

Symbols	Definitions
i	i-th synchronous generator
T'_{d0}	d-axis open-circuit time constants
T'_{q0}	q-axis open-circuit time constants
E_{fd}	Field voltage
X_d	Synchronous transient and sub-transient d-axis reactance
X_q	Synchronous transient and sub-transient q-axis reactance
ω_s	Synchronous speed
ω	Rotor speed
T_E	Electrical torque
T_M	Mechanical torque or power output
V_{ref}	Excitation voltage reference
K_A	Static excitation gain
δ	Generator rotor angle
H	Inertia constant
D	Damping coefficient
R_s	Armature resistance
V_q	q-axis component of generator terminal voltage
V_d	d-axis component of generator terminal voltage
I_q	q-axis component of stator current
I_d	d-axis component of stator current
E'_q	Transient EMF due to flux linkage in q-axis damper coil
E'_d	Transient EMF due to flux linkage in d-axis damper coil

where

$$\begin{gathered} V_d = [V_{d1} \ \dots \ V_{dm}]^T, V_q = [V_{q1} \ \dots \ V_{qm}]^T \\ E'_d = [E'_{d1} \ \dots \ E'_{dm}]^T, E'_q = \left[E'_{q1} \ \dots \ E'_{qm}\right]^T \\ I_d = [I_{d1} \ \dots \ I_{dm}]^T, I_q = [I_{q1} \ \dots \ I_{qm}]^T \end{gathered} \tag{9}$$

$$\begin{gathered} R_s = diag([R_{s1} \ \dots \ R_{sm}]) \\ X'_d = diag([X'_{d1} \dots X'_{dm}]) \\ X'_q = diag([X'_{q1} \dots X'_{qm}]) \end{gathered} \tag{10}$$

Considering an infinite bus system, n number of machines and k number of loads the power system network equations are:

$$\begin{bmatrix} I_s \\ I_G \\ I_L \end{bmatrix} = \begin{bmatrix} V_{SS} & V_{SG} & V_{SL} \\ V_{GS} & V_{GG} & V_{GL} \\ V_{LS} & V_{LG} & V_{LL} \end{bmatrix} \begin{bmatrix} V_s \\ V_G \\ V_L \end{bmatrix} \tag{11}$$

With n machines, the loads in the power system can be described as a constant impedance, hence keeping the load impedance zero. A reduction order can be used to reduce the elements that are load related from the admittance matrix of the lines network. Machine equations interfacing network equations are:

$$\begin{gathered} T_\delta\left(I_d + jI_q\right) = I_G \\ T_\delta\left(V_d + jV_q\right) = V_G \\ T_\delta = diag\left(\left[e^{j(\delta_1 - \frac{\pi}{2})} \dots e^{j(\delta_m - \frac{\pi}{2})}\right]\right) \end{gathered} \tag{12}$$

From the above equation of differential algebra, the nonlinear behavior of the power system can be modeled, and the ordinary differential equations are used as the solver to solve and represent the equations. Figure 4 shows the single-line diagram of a single-machine infinite bus power system.

3.2 DFIG In a Multimachine Power System

Integrating a DFIG WECS even to a single machine infinite bus results in a multi-machine power system. This integration comes with various challenges. The stochastic nature of WECS limits its behavior to that of a conventional synchronous generator. One factor that is used to evaluate WECS efficiency in multi-machine is its ability to provide ancillary services especially power oscillation damping (POD) and Temporary frequency response (TFR). These two operations help improve the stability of the power grid system [33].

In a multi-machine system, inter-area oscillation is the considered mode of oscillation. Oscillations not only cause power system instability but also limit power transfer capability during fault condition. Exciting grid codes did not include power system oscillation damping as an ancillary service offered by WECS, though its incorporation is expected in near future [34]. Synchronous generators in the conventional grid damp oscillations using the popular PSS, but this damping controller may not be enough with increased penetration of wind energy to the grid. Research in [33, 35] has revealed that DFIG-based WECS are able to interact with the synchronous generator PSS. It was observed that power electronic converters of the DFIG WECS can provide oscillation damping by providing a decoupling control between reactive and active powers. These internal oscillation damping is achieved through proper with the DFIG back-to-back converters. POD concept is widely utilized by combining PSS and FACTS [33].

4. OSCILLATION AND STABILITY IN THE POWER SYSTEM

Although the power system stability is basically a single problem, classifying it as such prevents us from understanding and effectively addressing the different instabilities that a power system may experience. Classifying stability into proper categories makes it much easier to analyze stability by identifying the major causes of instability and coming up with solutions to enhance stable operation [36]. Therefore, classification is crucial for thorough practical study and to offer a better solution to power system stability issues. The focus of this review as regards power system stability is rotor angle stability challenges mostly due to oscillations in the power system. Figure 5 shows the classification of power system stability.

4.1 Power System Oscillation

Rotor angle stability is the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. It depends on the capacity of each synchronous machine in the system to maintain or restore equilibrium between electromagnetic torque and mechanical torque. Increased angular swings of some generators which cause them to lose synchronism with other generators are issues relating to angular stability. The rotor angle stability problem involves the study of electromechanical oscillations inherent in power systems [36]. Oscillations in power system is an inherent phenomenon in synchronous generators, which leads to variation in output power as the rotors rotate at synchronous speed.

The non-linear nature of synchronous generators is the major contributing factor to oscillations in the power system, which is an inherent feature of an integrated power grid system. Any incidence or disturbance in the power system can lead to oscillations in the power grid system which occur as a series of related events in a synchronous generator [36]. Under normal operating conditions, the synchronous generator rotor speed is maintained at synchronism by the mechanical and electromagnetic torque balance. Any perturbation that upsets the equilibrium causes the rotor's speed to change which means decelerating or accelerating from its synchronous speed. A phenomenon known as the swing equation in [36] best describes this situation. Power system oscillations may impact the power system stability of the entire power grid system, and millions of people could experience power disruptions if the oscillations are not adequately dampened. Table 2 presents some of the recent notable power system oscillation occurrences which led to power outages.

4.2 Dynamics of Rotor

Speed deviation in rotor results in a change in rotor angle. This change further leads to variations in output power generated. This is best described by power angle characteristics in [36] and these sequential events culminate in power system oscillations. Electrical and mechanical torque imbalance in synchronous generators give rise to these oscillations and thus are named electromechanical oscillations and the frequency range is usually 0.2 - 3 Hz [43]. Generally, power system oscillations are classified based on electromechanical modes of oscillations which are of two types: local area modes and inter-area modes of oscillations.

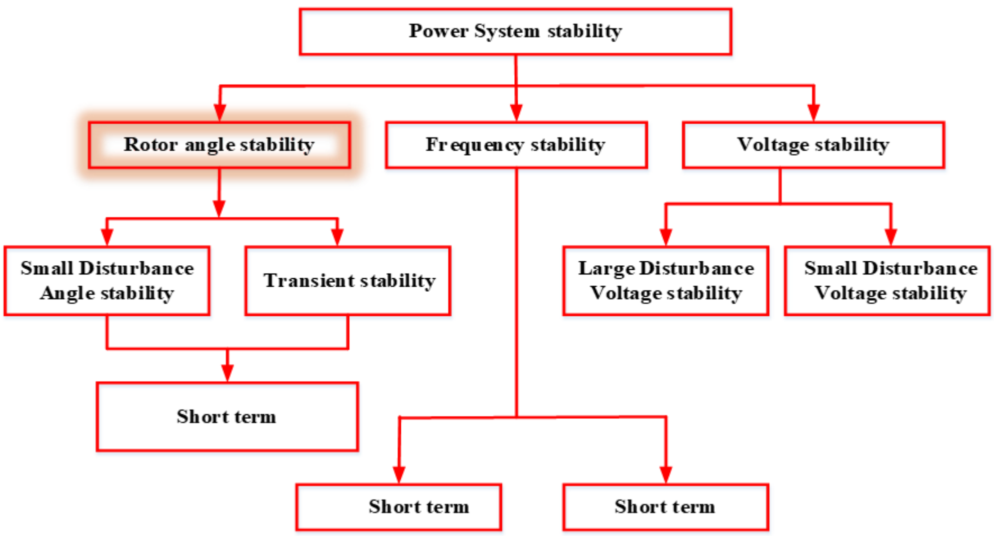

Figure 5. Classification of power system stability [37]

Table 2. List of recent notable power system oscillation occurrences which led to power outages

Year of occurrence	Date of occurrence	Country	Total number of people affected (millions)
2015 [38]	January 26	Pakistan	140
2015 [39]	March 31	Turkey	70
2016 [38]	August 17	Sri Lanka	21
2019 [40]	March 7	Venezuela	30
2019 [41]	June 16	Argentina, Paraguay, Uruguay	48
2019 [42]	August 4-5	Indonesia	100

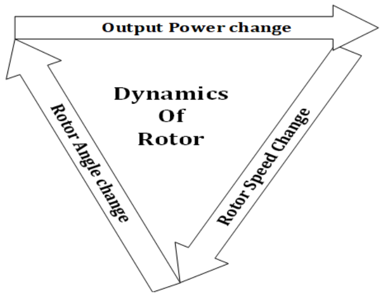

Figure 6. Series of events in rotor dynamics [5]

- Local area modes: local area modes of oscillations occur in generators in the same region. There are small cycle oscillations with high frequency in the range of 0.8 – 3.0 Hz [44]. Inter-area modes of oscillations occur coherently among generators in different regions connected via the transmission tie line. There are long cycle oscillations with a low frequency of 0.2 – 0.7 Hz [45].
- Inter-area mode presence is typical in an integrated power grid system with long transmission lines and compared to local area modes of oscillation, inter-area modes of oscillation have severe impacts on power system stability because there occur between two regions. Figure 6 shows a series of sequential events in rotor dynamics.

5. DAMPING CONTROLLERS

Power system oscillation incidents occur without prior warning. Design of automated control and proper detecting schemes are incorporated into the system to dampen these oscillations. Various methods of damping and modeling of these damping methods to reduce oscillations in the power grid system. Damping methods used in the power system can be broadly classified into four categories, namely, the PSS damping method, FACTS damping method, a combination of PSS and FACTS called coordination damping method, and most recently machine learning damping. Figure 7 shows various damping schemes and damping controllers under each scheme.

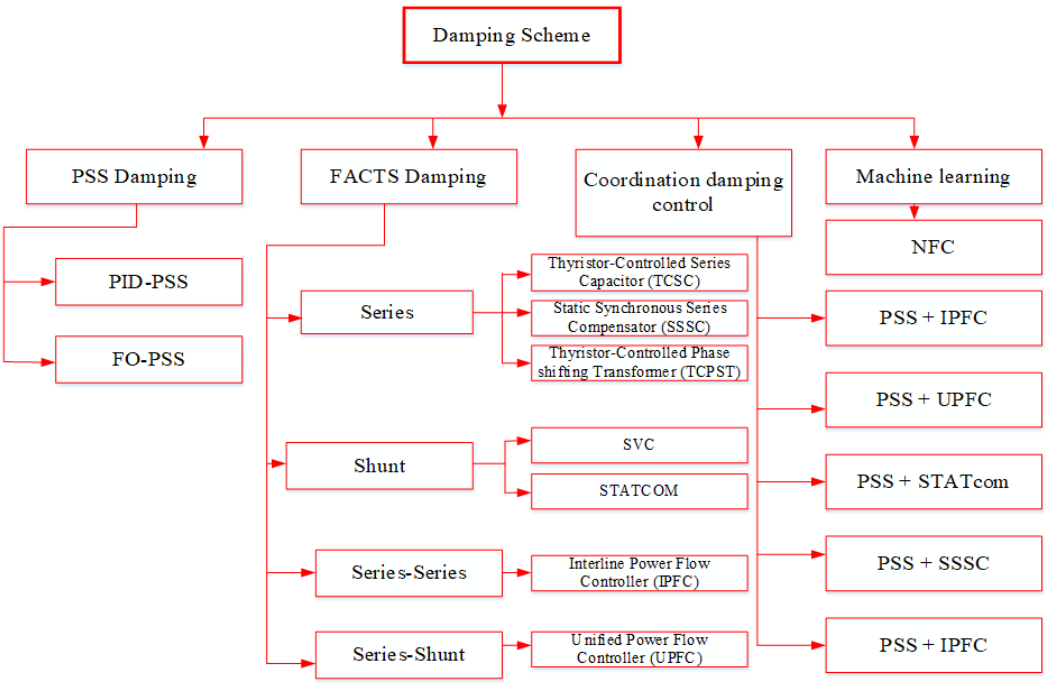

Figure 7. Power system oscillation damping schemes [5]

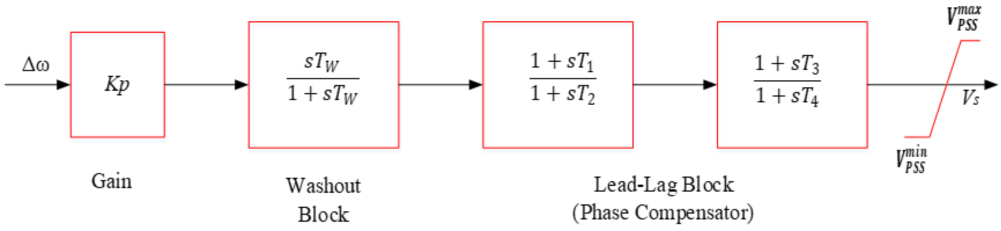

Figure 8. A lead-lag PSS [46, 47]

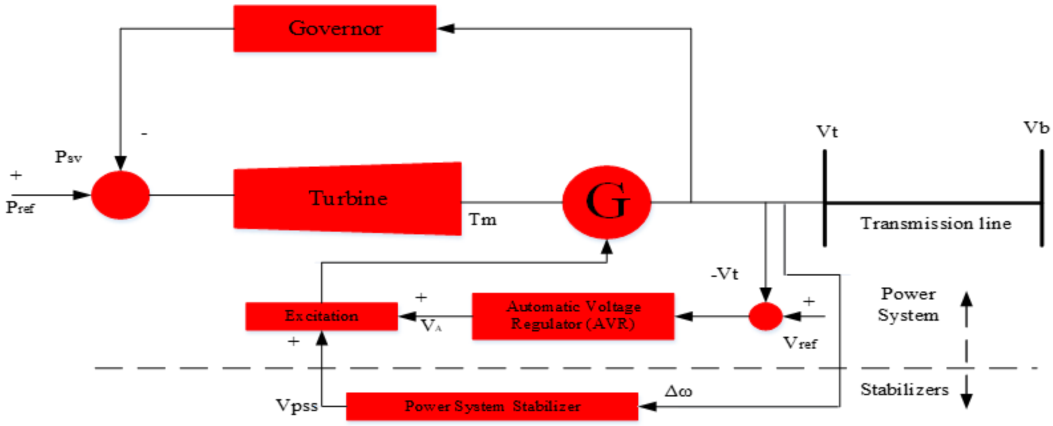

Figure 9. A synchronous generator with PSS connected through its excitation system [46]

5.1. Power System Stabilizer (PSS)

The concept of PSS was first introduced in 1969 as an important and economical dampening strategy for power system stability. The excitation voltage can be controlled to vary the output power produced, following the theory of synchronous machines. The PSS is installed to give the synchronous generator's excitation system an additional input signal. PSS adds an extra synchronizing torque that is phase-locked to the speed deviation. As a result, the system stability is constrained, and the growing oscillations are dampened. PSS can dampen local electromechanical modes of oscillation as well as inter-area electromechanical modes of oscillation if properly designed [5]. PSS coordination with other classical controllers like proportional integral derivative (PID) can also be implemented for effective damping. For example, PID-PSS on SMIB was developed by [46]. Figure 8 shows a conventional lead-lag PSS, while Figure 9 shows a synchronous generator with PSS connected through its excitation system.

5.2. Flexible Alternating Current Transmission System (FACTS)

Over the last decade, power electronic converters' main features which are current, voltage, and switching frequency have significantly improved, thus enabling the development of many FACTS devices [48]. As the name implies, FACTS devices offer flexibility on an inflexible transmission line and aid the injection of reactive power at a bus. Primarily, FACTS is used to enhance the power transfer capability of the transmission line, but recently researchers and power engineers have been attracted to FACTS ability to dampen oscillations [49].

Renewable power sources like offshore wind systems are located in the sea and integration into the grid is done through very long transmission lines. Therefore, the oscillation dynamics in an integrated power grid system is very complex. PSS implementation only cannot easily damp inter-area modes (with low frequencies in the range of 0.8-3.0 Hz) of oscillation. FACTS devices are normally classified based on their connection approach to the transmission line: series-connected devices (thyristor-controlled series compensator TCSC, Static synchronous series compensator SSSC, gate-controlled series capacitor GCSC), shunt-connected (Static VAR compensator SVC, STATic COMpensator STATCOM) shunt- and series-connected devices (unified power flow controller UPFC) and most recently series-series connected devices (Interline power flow controller, IPFC). FACTS absorbs or injects reactive power to the transmission line by the proper firing of its thyristor gate and adjusting the capacitor banks and reactor stacks [50]. FACTS damping performance relies on properly designing its damper known as power oscillation damper (POD). Figure 10 shows the distribution of publications on FACTS device application in a wind-integrated grid system from 2014 to 2022. The SSSC distribution of publications is about 34%, which has the highest percentage in terms of series FACTS devices. Besides, STATCOM has the highest percentage (18%) in distribution of publication in terms of shunt FACTS devices. The functional diagrams of SSSC, STATCOM, and IPFC are shown in Figure 11.

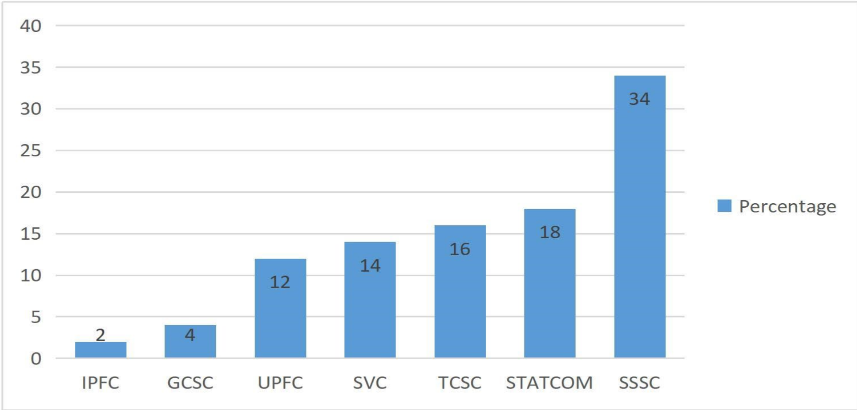

Figure 10. Distribution of publications on FACTS device application in a wind-integrated grid system

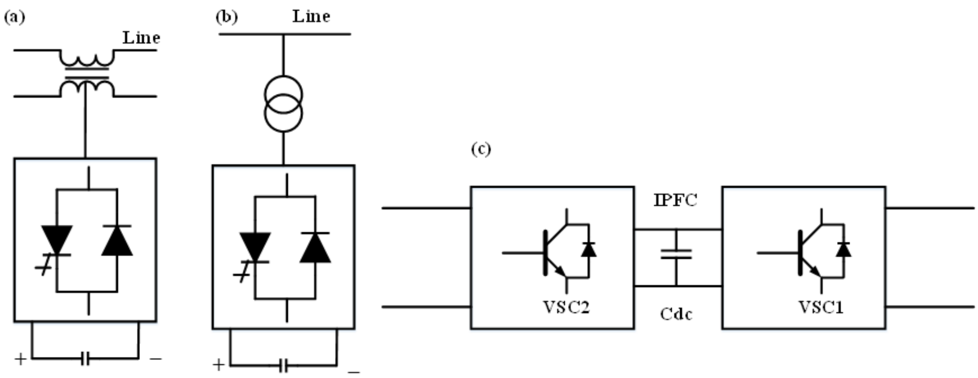

Figure 11. (a) SSSC, (b) STATCOM [5], (c) IPFC [9]

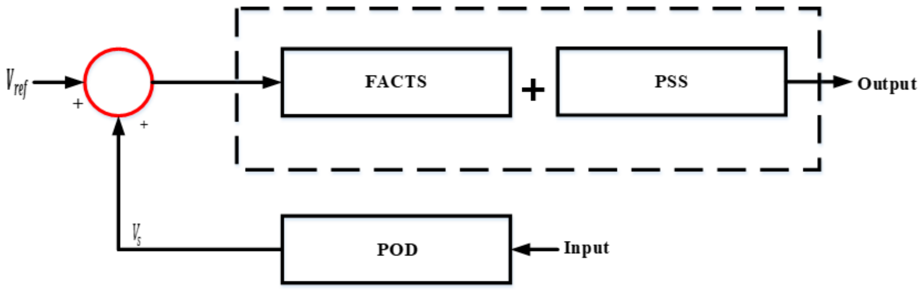

Figure 12. Coordination between FACTS device and corresponding damping controller [5]

5.3. Coordination Control Damping

To effectively dampen different electromechanical oscillation modes, PSS and FACTS are combined, although this combination between various controllers can adversely affect power system damping over specific electromechanical modes and may disrupt the system if the combination or coordination is not properly designed. Coordination of PSS and FACTS have been carried out in various studies. Coordination design for PSS and SVC was done in [51], PSS and TCSC coordination in [52], and PSS-UPFC and PSS-IPFC coordination in [53, 54]. The purpose of damping controller coordination schemes is to design a robust damping scheme over an oscillation. Figure 12 shows the coordination between the FACTS device and any corresponding damping controller.

5.4. Machine Learning (ML)

ML damping scheme has been the research focus in recent times. It is now popular because of the tremendous achievements of neural networks and reinforcement learning. Reinforcement learning is a branch of ML that investigates ways to use past data to improve future management of dynamic systems [55]. ML methods require the empirical approximation of an unknown model of some system, such as the dynamics of robot manipulators or sensor transduction behavior [56]. Although neural networks are frequently used in this process to approximate functions, the term is very applicable to many optimization techniques and other data-driven methods [56].

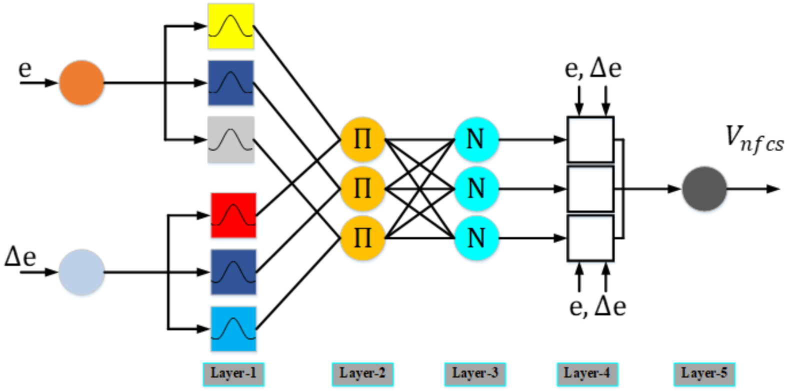

Figure 13. Two-input Sugeno-type NFC structure [57]

ML or artificial intelligent controllers have the ability to learn, adapt and improve the performance of the environment where it is applied. A neuro-fuzzy controller (NFC) was used in [57] to replace the work of PSSs and provide superior properties to the conventional PSSs and FACTS stabilizers in controlling low-frequency oscillations in the power system. NFC structure is a combination of the adaptability feature of artificial neural networks, its generalization and learning ability, and fuzzy logic controller as well. A model-free design is the most relevant feature of the neuro-fuzzy controller [9]. Figure 13 shows a two-input Sugeno-type NFC structure which is one of the most common fuzzy logic models.

6. SYSTEM LINEARIZATION TECHNIQUE

The power system stability study specifically helps in reviewing the damping controller design process. Conducting a stability study requires modeling the power system's dynamic characteristics. This power system's dynamic model uses nonlinear, linear, and differential equations (ODE) [58]. Nonlinear ODE can be used to represent the dynamics of a power system as:

$$\dot{x}(t) = f\big(x(t), u(t)\big) \tag{13}$$
$$y(t) = g\big(x(t), u(t)\big) \tag{14}$$

where f and g= nonlinear functions, y = output vector, u= input vector and x = the state vector. The system states at equilibrium and the input vectors can be expressed as:

$$x_0 = f(x_0, u_0) = 0 \tag{15}$$

The small deviation following a perturbation from the system equilibrium and expanding using Taylor's series around the equilibrium and input vectors, finally the state space equation of a linear system can be represented as:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{16}$$
$$y = Cx(t) + Du(t) \tag{17}$$

where A, B, C and D are state, input, output and feedforward matrices.

The state space model is referred to as linear time-invariant (LTI). By linearizing nonlinear ODEs around an operational point to a set of first-order linear differential equations, the LTI state space model is developed. Linearization is done as it helps to check local stability and understand power system dynamics to speed up power system simulation. There are toolboxes in MATLAB®/SIMULINK® for linear controller design such as the power system toolbox (PST) developed by Rogers [59], PSAT, Mat Dyn [60], MatSim [32]. These are toolboxes used by researchers in designing damping controllers and to analyze power system oscillation. Figure 14 shows the procedure for damping controller design and performance evaluation.

6.1 Integral Time-Based Error

In the time-based error function of the damping controller, the error is defined as the deviation of the rotor speed of the generator from its nominal value [61] [62]. Thus, the objective functions can be defined as Integral time absolute error (ITAE), Integral square error (ITSE), Integral absolute error (IAE), integral square time square error (ISTSE) and Integral square error (ISE). The index value must always be positive or zero value and the system with the lowest index defines as the best system.

The objective function is to minimize (ITAE or ITSE or IAE or ISE or ISTSE)

$$ITAE = \int_0^t t(|\Delta\omega_i|)dt \tag{18}$$

$$ITSE = \int_0^t t(|\Delta\omega_i|)^2 dt \tag{19}$$

$$IAE = \int_0^t (|\Delta\omega_i|)dt \tag{20}$$

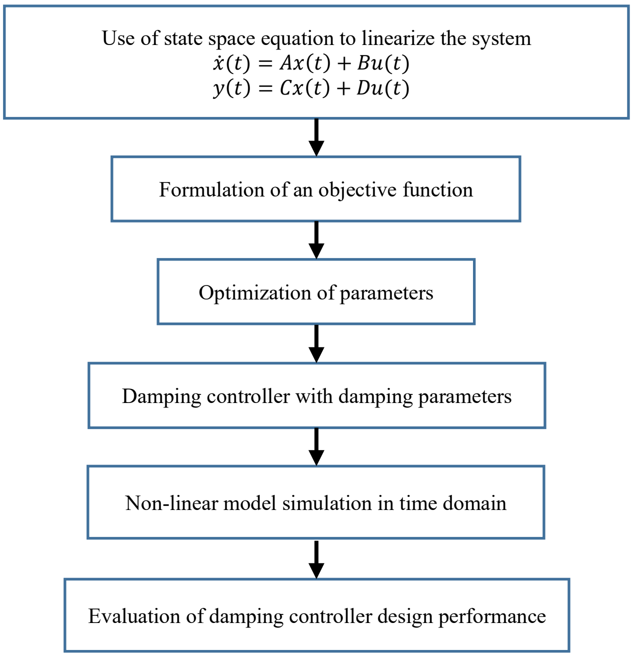

Figure 14. Procedure for damping controller design and performance evaluation [5]

$$ISE = \int_0^t (\Delta\omega_i)^2 dt \tag{21}$$

$$ISTSE = \int_0^t (t|\Delta\omega_i|)^2 dt \tag{22}$$

Subject to

$$K_{imin} \leq K_i \leq K_{imax} \tag{23}$$

$$T_{imin} \leq T_i \leq T_{imax} \tag{24}$$

where $\Delta\omega_i$ the rotor speed deviation, T_i is the time constant and K_i is the gain.

6.2 Eigenvalue-Based Function

A linearized power system is stable when its eigenvalues are located on the left region of a complex s-plane. Analysis of the eigenvalues is used to determine the system's stability using:

$$(\lambda_i = \sigma_i \pm j\omega_i) \tag{25}$$

where $\lambda_i = eig(A)$ can be used to represent the eigenvalues of the state matrix (A) where $i = 1,2,3, \dots, n$. the number of state variables in the system is n which is also equal to the sum of all the eigenvalues. The built-in function in MATLAB® is used to calculate the system eigenvalues.

In the theory of advanced control systems, the stability of a system can be determined easily based on the location of eigenvalues on the complex s-plane, as shown in Figure 15. If all the eigenvalues are on the left side of the s-plane, then the system is deemed stable, but if any eigenvalue is on the right side, then the system is unstable. Shifting the eigenvalues to the left side is the main objective of optimizing the damping controller parameters. The definition of the objective function is necessary before the optimization technique is used to shift the eigenvalues from the right to the left, which is the stable zone. The formulation of objective functions and optimization strategies are discussed in the next section.

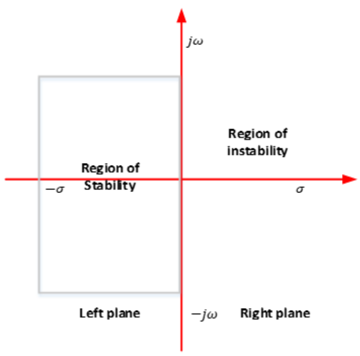

Figure 15. Stability criteria for system eigenvalues in a complex s-plane [63]

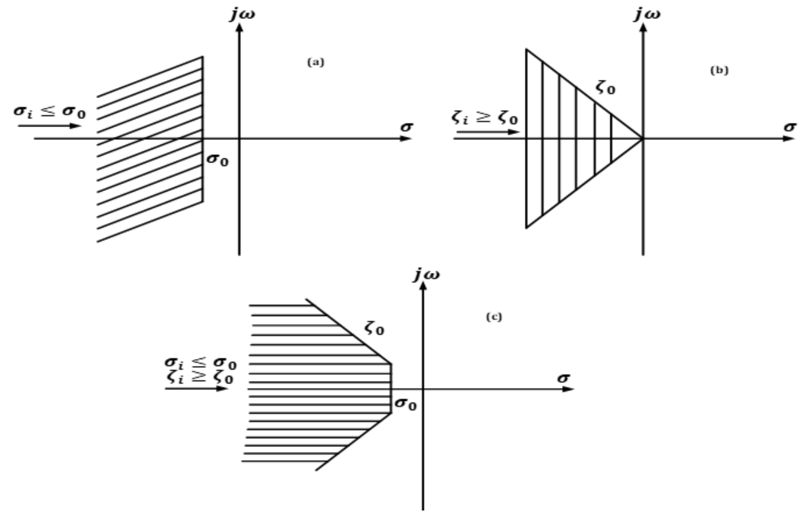

Figure 16. Approaches for objective function formulation: (a) formulation based on damping factor, (b) formulation based on damping ratio, (c) formulation based on both damping factor and damping ratio (D-shape) [63]

7. FORMULATION OF OBJECTIVE FUNCTION

Robust damping controller design involves the application of objective functions with different formulations. Formulation of the objective function is a very critical aspect of designing a damping controller. In the integral time error-based function, the objective function is to minimize the rotor speed deviation error (Δω) using the various integral error functions. The index value must always be positive or zero value and the system with the lowest index defines the best system.

In eigenvalue analysis, eigenvalues are moved from the unstable region to the stable region in the complex *s*-plane by the objective function. The two types of objective functions here are singular objective functions and multiple objective functions. Particularly, objective functions are calculated from the real (σ_i) and imaginary (ω_i) parts of the system eigenvalues and stated in terms of damping ratios and damping factors as:

$$\text{Damping factor } \sigma_i = real(\lambda_i) \quad (26)$$

$$\text{Damping ratio } \zeta_i = -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \quad (27)$$

Figure 16 depicts the objective function formulation based on the damping ratio and factor.

7.1 Singular Objective Function

When a function has a singular objective, its mathematical expression is aimed at accomplishing that singular target during optimization. The singular objective function is described in terms of the damping factor or damping ratios of electromechanical modes. In [64-66], the damping ratio determines the oscillation amplitude decay rate. Thus, the damping ratio was maximized for faster oscillation attenuation through optimization of the controller parameters.

7.2 Multiple Objective Function

In this formulation, the multiple objective function seeks to accomplish two or more objectives that is the damping factor and the damping ratio. While the damping ratio improves oscillation settling time, the damping factor is associated with a reduction in oscillation overshoot. Consequently, both lead to a robust damping controller design and are incorporated into multiple objective functions. The formulation required to arrange eigenvalues in a D-shaped zone is formed by this combination, which creates a D-shaped stability area.

Table 3 shows an overview of the different formulations of the objective function, i is an $\in \{1,2,3, \dots, n\}$ and j is an $\in \{1,2,3, \dots, p\}$ are the eigenvalues and operating points of the system during optimization. n is the total number of system's eigenvalues while p is the total number of operating points considered.

8. OPTIMIZATION TECHNIQUES FOR DAMPING CONTROLLER DESIGN

Considering how frequently and fundamentally it is used in the majority of engineering tasks, optimization has emerged as one of the most significant mathematical strategies. The key to success in any subject is constant development. Any system's performance can be increased by having a full understanding of all the variables that influence it. By enhancing the efficiency of the system, it is possible to get the finest outcomes using the resources at hand. A technique for optimization makes the best decisions within a given set of constraints and aims to find the most effective solution out of all those that are conceivable [67]. Optimization techniques include conventional, deterministic techniques, and most recently heuristic and metaheuristic algorithms. Heuristic and metaheuristic techniques are defined as:

Table 3. Methods used in objective function formulation

Objective function type	Equation formulation	Main objective
Singular objective function	Max $\{real(\lambda_{ij})\}$	Minimization
	Min (ζ_{ij})	Maximization
	$\sum_{i=1}^{n}(1-\zeta_{ij})$	Minimization
Multiple objective function	$\sum_{j=1}^{np}\sum_{\sigma_{ij}\geq\sigma_0}(\sigma_0-\sigma_0)^2+a\sum_{j=1}^{np}\sum_{\zeta_{ij}\leq\zeta_0}(\zeta_0-\zeta_0)^2$	Minimization
	$-max(\sigma_{ij})+\min\zeta_{ij})$	Maximization

- **Heuristic techniques:** Heuristic techniques are algorithms inspired by nature that mostly find a solution through trial and error using a randomization approach.

- **Metaheuristic techniques:** Metaheuristic technique is an improved version of the heuristic technique is metaheuristic technique, also nature-inspired like heuristics but is more flexible, and robust and does not get its initial solution through prediction [68]. These algorithms can be categorized into five main categories: nature-based methods, physics-based methods, swarm-based methods, human-based methods, and animal-based methods. Figure 17 summarizes various optimization techniques available for damping controller design.

9. CONCLUSION AND RECOMMENDATION

Power system oscillations in an integrated power grid system is a challenge that reduces power transfer capability, puts the environment at risk, and leads to blackout and collapse of the entire integrated system. Thus, an effective damping controller is very important in mitigating power system oscillation challenges. Different damping controller designs, like PSSs, and FACTS have in recent years been explored through the formulation of objective functions and different optimization techniques to improve the dynamic stability of the power system and increase damping controller efficiency. However, the design of a robust damping controller for a DFIG wind-integrated system is a daunting task because it is considered a multi-phase optimization issue and is very difficult to address when using traditional optimization techniques.

This review focused on this issue by introducing the WECS, and integration to a single-machine and multi-machine systems. Classification and fundamental principles of power system oscillations inherent in an integrated system. Damping controller schemes commonly deployed are reviewed as regards their merits and demerits. By reviewing the different damping controller schemes, it is observed that SSSC which is a series-connected FACTS damping controller, and STATCOM, a shunt-connected FACTS damping controller are widely deployed in a wind-integrated system to achieve effective oscillation damping. System linearization technique was also discussed, and some commonly used toolbox for simplifying the non-linear

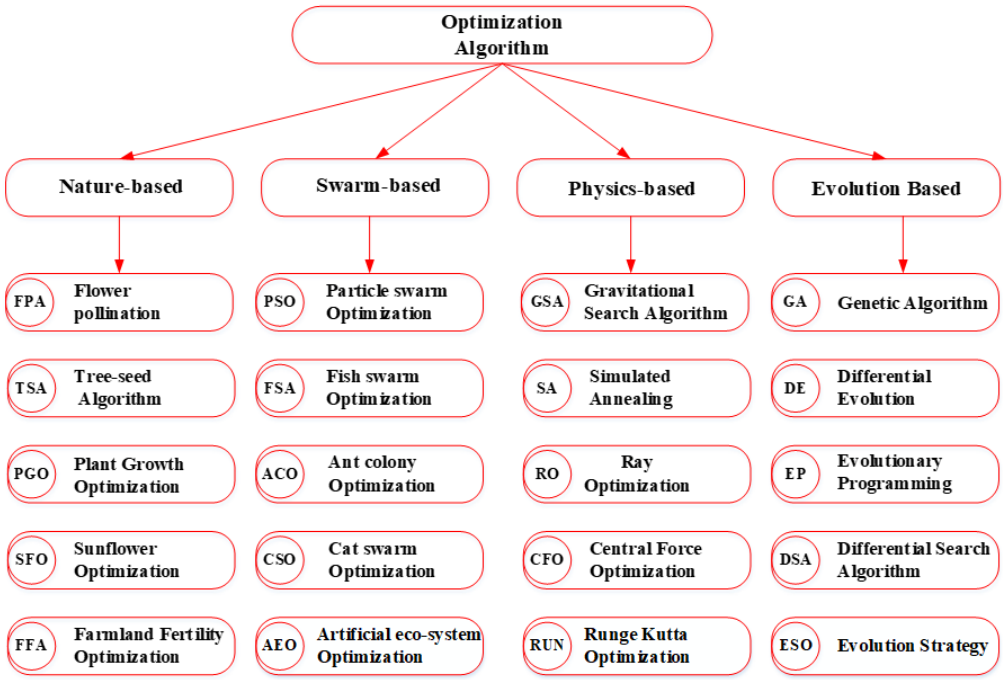

Figure 17. Summary of meta-heuristic techniques [12]

model was listed. Integral time error-based function and eigenvalue-based approaches for the formulation of the objective function are summarized and reviewed. Comparative analysis requirement for different formulation approaches was also discussed. Finally, various optimization techniques applied in the design of the damping controller were categorized and presented. In highlighting these issues, some suggestions for efficient damping controller design and development in an integrated power system to address the problems include:

- Statistically analyzing the convergence curve and applying to the optimized damping controller for proper justification.
- Proper objective function formulation in the design of damping controller significantly contributes to increased oscillation damping.
- Recent optimization algorithms such as ML with an example of neuro-fuzzy discussed needs to be explored with increasing penetration of renewables (wind) to the power system grid.

This review discussed the different damping controllers, procedures for damping controller design, and suggestions for the design of a robust damping controller. Further research in the advancement of damping controller design especially incorporating machine learning in an integrated system are provided, and these include (i) machine learning (ML) damping schemes such as neuro-fuzzy controller presented in [57], (ii) PSS and FACTS coordination design, (iii) damping controller design for wind energy integrated into a large power system.

ACKNOWLEDGMENT

This review is supported by Department of Electrical/Electronic Engineering, Faculty of Engineering and Technology Nigeria Defence Academy through Center for Power System Dynamic Simulation.

REFERENCES

[1] A. Sabo and N. I. A. Wahab, Rotor angle transient stability methodologies of power systems: A comparison, in *2019 IEEE Student Conference on Research and Development (SCOReD)*, Bandar Seri Iskandar, Malaysia, 2019, 1-6.

[2] S. D. Ahmed, F. S. M. Al-Ismail, M. Shafiullah, F. A. Al-Sulaiman and I. M. El-Amin, Grid integration challenges of wind energy: A review, *IEEE Access*, 8, 2021, 10857-10878.

[3] H. E. Murdock *et al.*, Renewables 2021- Global status report, 2021.

[4] S. W. Xia, S. Q. Bu, X. Zhang, Y. Xu, B. Zhou and J. B. Zhu, Model reduction strategy of doubly-fed induction generator-based wind farms for power system small-signal rotor angle stability analysis, *Applied Energy*, 222, 2018, 608-620.

[5] M. A. Hannan *et al.*, Artificial intelligent based damping controller optimization for the multi-machine power system: A review, *IEEE Access*, 6, 2018, 39574-39594.

[6] L. Wang, Q. -S. Vo and A. V. Prokhorov, Stability improvement of a multimachine power system connected with a large-scale hybrid wind-photovoltaic farm using a supercapacitor, *IEEE Transactions on Industrial Applications*, 54(1), 2017, 50-60.

[7] W. Khawaja, N. A. M. Kamari and M. A. A. M. Zainuri, Design of a damping controller using a metaheuristic algorithm for angle stability improvement of an MIB system, *Applied Sciences*, 12(2), 2022, 589.

[8] A. Sabo *et al.*, Artificial intelligence-based power system stabilizers for frequency stability enhancement in multi-machine power systems, *IEEE Access*, 9, 2021, 166095-166116.

[9] A. Sabo, N. I. Abdul Wahab, M. L. Othman, M. Z. A. Mohd Jaffar, H. Beiranvand and H. Acikgoz, Application of a neuro-fuzzy controller for single machine infinite bus power system to damp low-frequency oscillations, *Transactions of the Institute of Measurement and Control*, 43(16), 2021, 3633-3646.

[10] T. K. Roy, S. K. Ghosh, M. S. Anower, M. A. Mahmud, R. Kumar and A. Saxena, Mitigation of SSR in series-compensated DFIG-based wind farms with STATCOMs using a nonlinear backstepping control scheme, in *2020 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, Jaipur, India, 2020, 1-6.

[11] D. K. Sambariya and R. Prasad, A novel fuzzy rule matrix design for fuzzy logic-based power system stabilizer, *Electric Power Components and Systems*, 45(1), 2017, 34-48.

[12] M. A. El-Dabah, S. Kamel, M. Khamies, H. Shahinzadeh and G. B. Gharehpetian, Artificial gorilla troops optimizer for optimum tuning of TID based power system stabilizer, in *2022 9th Iranian Joint Congress on Fuzzy and Intelligent Systems (CFIS)*, Bam, Iran, 2022, 1-5.

[13] S. M. Almufti, Lion algorithm: Overview, modifications and applications, *International Research Journal on Science, Technology, Education, and Management*, 2(2), 2022, 176-186.

[14] N. Muisyo, C. M. Muriithi and S. I. Kamau, Enhancing low voltage ride through capability of grid connected DFIG based WECS using WCA-PSO tuned STATCOM controller, *Heliyon*, 8(8), 2022, e09999.

[15] K. Palanimuthu, G. Mayilsamy, S. R. Lee, S. Y. Jung and Y. H. Joo, Fault ride-through for PMVG-based wind turbine system using coordinated active and reactive power control strategy, *IEEE Transactions on Industrial Electronics*, 2022, 1-11.

[16] J. Bhukya and V. Mahajan, Optimization of damping controller for PSS and SSSC to improve stability of interconnected system with DFIG based wind farm, *International Journal of Electrical Power and Energy Systems*, 108, 2019, 314-335.

[17] A. S. Ali, K. K. Mehmood, S. Baloch and C. -H. Kim, Modified rotor-side converter control design for improving the LVRT capability of a DFIG-based WECS, *Electrical Power Systems Research*, 186, 2020, 106403.

[18] A. Alsakati, C. A. Vaithilingam, J. Alnasseir and A. Jagadeeshwaran, Simplex search method driven design for transient stability enhancement in wind energy integrated power system using multi-band PSS4C, *IEEE Access*, 9, 2021, 83913-83928.

[19] S. G. Sadhana, S. Ashok and S. Kumaravel, Small signal stability analysis of grid connected renewable energy resources with the effect of uncertain wind power penetration, *Energy Procedia*, 117, 2017, 769-776.
[20] M. Darabian, A. Bagheri and S. Behzadpoor, A UPFC-based robust damping controller for optimal use of renewable energy sources in modern renewable integrated power systems, *IET Generation, Transmission & Distribution*, 2022.
[21] T. -Z. Ang, M. Salem, M. Kamarol, H. S. Das, M. A. Nazari and N. Prabaharan, A comprehensive study of renewable energy sources: classifications, challenges and suggestions, *Energy Strategy Review*, 43, 2022, 100939.
[22] J. X. Jin, R. H. Yang, R. T. Zhang, Y. J. Fan, Q. Xie and X. Y. Chen, Combined low voltage ride through and power smoothing control for DFIG/PMSG hybrid wind energy conversion system employing a SMES-based AC-DC unified power quality conditioner, *International Journal of Electrical Power and Energy Systems*, 128, 2021, 106733.
[23] J. Mwaniki, H. Lin and Z. Dai, A condensed introduction to the doubly fed induction generator wind energy conversion systems, *Journal of Engineering*, 2017, 2918281.
[24] Bonfiglio, F. Delfino, F. Gonzalez-Longatt and R. Procopio, Steady-state assessments of PMSGs in wind generating units, *International Journal of Electrical Power and Energy Systems*, 90, 2017, 87-93.
[25] M. A. A. Bezerra, J. L. W. Oliveira, P. P. Praça, D. S. Oliveira, L. H. S. C. Barreto and B. R. de Almeida, Isolated AC-DC interleaved converter for MVDC collection grid in HVDC offshore wind farm, in *2019 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Anaheim, USA, 2019, 1926-1933.
[26] Z. Li, Q. Song, F. An, B. Zhao, Z. Yu and R. Zeng, Review on DC transmission systems for integrating large-scale offshore wind farms, *Energy Conversion and Economics*, 2(1), 2021, 1-14.
[27] G. Abeynayake, G. Li, J. Liang and N. A. Cutululis, A review on MVdc collection systems for high-power offshore wind farms, in *2019 14th Conference on Industrial and Information Systems (ICIIS)*, Kandy, Sri Lanka, 2019, 407-412.
[28] M. R. Islam, M. A. Rahman, K. M. Muttaqi and D. Sutanto, A new magnetic-linked converter for grid integration of offshore wind turbines through MVDC transmission, *IEEE Transactions on Applied Superconductivity*, 29(2), 2019, 1-5.
[29] P. Kou, D. Liang, Z. Wu, Q. Ze and L. Gao, Frequency support from a dc-grid offshore wind farm connected through an hvdc link: A communication-free approach, *IEEE Transaction on Energy Conversion*, 33(3), 2018, 1297-1310.
[30] M. A. PAi, P. W. Sauer and J. H. Chow, *Power system dynamics and stability with synchrophasor measurement and power system toolbox*, IEEE Press, 2018, 1-364.
[31] L. Kunjumuhammed, S. Kuenzel, and B. C. Pal, *Simulation of Power System with Renewables*. Academic Press, 2019.
[32] H. Beiranvand, E. Rokrok, M. R. Shakarami, A. Kumar, S. Gopalakrishna, and S. Mohanty, MatSim: a Matpower and Simulink based tool for power system dynamics course education, in *31th Power System Conference,* Tehran, Iran, 2016, 1-6.
[33] O. M. Kamel, A. Y. Abdelaziz and A. A. Zaki Diab, Damping Oscillation techniques for wind farm DFIG integrated into inter-connected power system, *Electric Power Components and Systems*, 48(14-15), 2020, 1551-1570.
[34] E. M. G. Rodrigues, G. J. Osório, R. Godina, A. W. Bizuayehu, J. M. Lujano-Rojas and J. P. S. Catalão, Grid code reinforcements for deeper renewable generation in insular energy systems, *Renewable and Sustainable Energy Reviews*, 53, 2016, 163-177.
[35] K. Thanpisit and I. Ngamroo, Power oscillation damping control by PSS and DFIG wind turbine under multiple operating conditions, *Turkish Journal of Electrical Engineering and Computer Sciences*, 25(5), 2017, 4354-4368.
[36] P. S. Kundur and O. P. Malik, *Power system stability and control*. McGraw-Hill Education, 2022.
[37] N. Hatziargyriou *et al.*, Definition and classification of power system stability - revisited & extended, *IEEE Transactions on Power Systems*, 36(4), 2020, 3271-3281.
[38] J. P. Desai, Analysis of power swings and blackouts, in *2021 IEEE Congreso Estudiantil de Electrónica y Electricidad (INGELECTRA)*, Valparaiso, Chile, 2021, 1-6.
[39] B. Firat, Integrative currents? Electrifying the Turkey-EU relations in times of blackout, in *Energy, Resource Extraction and Society*, Routledge, 2018, 177-195.
[40] Q. Zhao, X. Qi, M. Hua, J. Liu and H. Tian, Review of the recent blackouts and the enlightenment, in *CIRED 2020 Berlin Workshop (CIRED 2020)*, 2020, 312-314.
[41] G. Alvarez and M. J. Blas, Enhancing of the operational decisions in electric power systems under blackouts, in *2020 International Conference on Decision Aid Sciences and Application (DASA)*, Sakheer, Bahrain, 2020, 646-651.
[42] T. O. Priyono, Analisa optimalisasi PLTMG Senayan sebagai pengirim tegangan sistem pasca blackout Agustus 2019, *Jurnal Elektro*, 9(1), 2021, 45-54.
[43] A. Alsakati, C. A. Vaithilingam, J. Alnasseir, K. Naidu and G. Rajendran, Transient stability enhancement of grid integrated wind energy using particle swarm optimization based multi-band PSS4C, *IEEE Access*, 10, 2022, 20860-20874.
[44] H. Zamani, M. Karimi-Ghartemani and M. Mojiri, Analysis of power system oscillations from PMU data using an EPLL-based approach, *IEEE Transactions on Instrumentation and Measurement*, 67(2), 2017, 307-316.
[45] R. Xie and D. J. Trudnowski, Tracking the damping contribution of a power system component under ambient conditions, *IEEE Transactions on Power Systems*, 33(1), 2017, 1116-1117.
[46] A. Sabo, N. I. A. Wahab, M. L. Othman, M. Zurwatul and A. M. Jaffar, Novel farmland fertility algorithm based PIDPSS design for SMIB angular stability enhancement, *International Journal of Advanced Science and Technology*, 29(6), 2020, 873-882.
[47] A. Sabo, N. I. A. Wahab, M. L. Othman, M. Z. A. M. Jaffar and H. Beiranvand, Farmland fertility optimization for designing of interconnected multi-machine power system stabilizer, *Applications of Modelling and Simulation*, 4, 2020, 183-201.

[48] V. Kohan *et al.*, Use of flexible alternating current transmission system to improve power system operation – damping oscillation and power flow control, in *2021 IEEE 4th International Conference and Workshop Óbuda on Electrical and Power Engineering (CANDO-EPE)*, Budapest, Hungary, 2021, 113-118.

[49] S. Yu, T. K. Chau, T. Fernando, A. V Savkin and H. H. -C. Iu, Novel quasi-decentralized SMC-based frequency and voltage stability enhancement strategies using valve position control and FACTS device, *IEEE Access*, 5, 2016, 946–955.

[50] B. Bhattacharyya and S. Kumar, Approach for the solution of transmission congestion with multi-type FACTS devices, *IET Generation, Transmission &. Distribution*, 10(11), 2916, 2802-2809.

[51] T. Surinkaew and I. Ngamroo, Two-level coordinated controllers for robust inter-area oscillation damping considering impact of local latency, *IET Generation, Transmission &. Distribution*, 11(18), 2017, 4520-4530.

[52] S. Ekinci and B. Hekimoğlu, Coordinated design of TCSC and PSS by using PSO algorithm for enhancement of SMIB power system stability, *Batman Üniversitesi Yaşam Bilimleri Dergisi*, 7(1/2), 2017, 9-21.

[53] H. Naghshbandy and A. Faraji, Coordinated design of PSS and unified power flow controller using the combination of CWT and prony methods with the help of SPEA II multi-objective optimisation algorithm, *IET Generation, Transmission & Distribution,* 13(21), 2019, 4900-4909.

[54] A. Sabo, N. I. A. Wahab and M. L. Othman, Coordinated design of PSS and IPFC using FFA to control low frequency oscillations, in *2021 IEEE 19th Student Conference on Research and Development (SCOReD)*, Kota Kinabalu, Malaysia, 2021, 201-206.

[55] M. Fliess and C. Join, Machine learning and control engineering: The model-free case, in *Proceedings of the Future Technologies Conference*, Vancouver, Canada, 2020, 258-278.

[56] K. Chin, T. Hellebrekers and C. Majidi, Machine learning for soft robotic sensing and control, *Advanced Intelligent Systems*, 2(6) 2020, 1900171.

[57] A. Sabo, N. I. Wahab, M. L. Othman, M. Z. Mohd Jaffar, H. Acikgoz and H. Beiranvand, Application of neuro-fuzzy controller to replace SMIB and interconnected multi-machine power system stabilizers, *Sustainability*, 12(22), 2020, 9591.

[58] Osipov and K. Sun, Adaptive nonlinear model reduction for fast power system simulation, *IEEE Transactions on Power Systems*, 33(6), 2018, 6746-6754.

[59] F. Milano, An open source power system analysis toolbox, *IEEE Transactions on Power Systems*, 20(3), 2005, 1199-1206.

[60] S. Cole and R. Belmans, MATFYN, a new matlab-based toolbox for power system dynamic simulation, *IEEE Transactions on Power Systems*, 26(3), 2011, 1129-1136.

[61] H. K. Abdulkhader, J. Jacob and A. T. Mathew, Fractional-order lead-lag compensator-based multi-band power system stabiliser design using a hybrid dynamic GA-PSO algorithm, *IET Generation, Transmission & Distribution*, 12(13), 2018, 3248-3260.

[62] A. Sabo, N. I. A. Wahab, M. L. Othman and M. Z. A. M. Jaffar, Mitigation of Oscillations in SMIB using a novel farmland fertility optimization based PIDPSS, in *2020 2nd International Conference on Smart Power & Internet Energy Systems (SPIES)*, Bangkok, Thailand, 2020, 234-239.

[63] S. Bayu, B. Khan, Z. M. Ali, Z. M. Alaas and O. P. Mahela, Mitigation of low-frequency oscillation in power systems through optimal design of power system stabilizer employing ALO, *Energies*, 15(10), 2022, 3809.

[64] K. Zhang, Z. Shi, Y. Huang, C. Qiu, and S. Yang, SVC damping controller design based on novel modified fruit fly optimisation algorithm, *IET Renewable Power Generation*, 12(1), 2018, 90-97.

[65] M. Gheisarnejad, An effective hybrid harmony search and cuckoo optimization algorithm based fuzzy PID controller for load frequency control, *Applied Soft Computing*, 65, 2018, 121-138.

[66] Y. Chen *et al.*, Optimized design method for grid-current-feedback active damping to improve dynamic characteristic of LCL-type grid-connected inverter, *International Journal of Electrical Power & Energy Systems*, 100, 2018,19-28.

[67] M. Fahim-Ul-Haque, M. R. Islam, M. Shafiullah and M. S. Hossen, Stability enhancement of single machine infinite bus system with UPFC using bat algorithm, in *2022 31st Conference of Open Innovations Association (FRUCT)*, Helsinki, Finland, 2022, 51-57.

[68] W. Khawaja, N. A. M. Kamari and M. A. A. M. Zainuri, Design of a damping controller using the sca optimization technique for the improvement of small signal stability of a single machine connected to an infinite bus system, *Energies*, 14(11), 2021, 2996.