Vokasi Unesa Bulletin of Engineering, Technology and Applied Science (VUBETA)
https://journal.unesa.ac.id/index.php/vubeta
Vol. 2, No. 2, 2025, pp. 148~174 DOI: 10.26740/vubeta.v2i2.34749
ISSN: 3064-0768

Modelling and Simulation of Damping Controller in DFIG and PMSG Integrated with A Convectional Grid: A Review

Sabo Aliyu[1], Dahiru Dauda[2*], Noor Izri Abdulwahab[3]
[1,2,3]Department of Electrical Engineering, Faculty of Engineering and Engineering Technology, Nigerian Defence Academy (NDA), Kaduna, Nigeria.
[3]Advanced Lightning Power and Energy Research (ALPER) Department of Electrical and Electronic Engineering, Universiti Putra Malaysia Serdang, Malaysia

Article Info

Article history:

Received September 04, 2024
Revised December 04, 2024
Accepted May 10, 2025

Keywords:

WECs
Generators
Damping controller
Stability
Optimization

ABSTRACT

Wind energy conversion systems stand out as one of the most abundant sources of energy provided by nature. These systems are highly sustainable and environmentally friendly, as they do not generate pollution. Damping controllers are specifically designed to enhance the robustness and adaptability of hybrid systems utilizing permanent magnet and double-fed induction synchronous generators. These generators are carefully integrated with conventional energy sources, necessitating a vigilant focus on grid stability, particularly rotor angle stability. This stability is crucial for preventing mechanical oscillations and potential disruptions in the grid caused by instability. Furthermore, power system stabilizers with excitation systems are carefully designed and optimized to maximize damping performance while minimizing energy losses. In this context, damping controllers play a vital role.

1. INTRODUCTION

Due to increasing energy demands and global warming, the shift from fossil fuels to clean energy sources is accelerating. The global installed capacity grew at a compound annual growth rate (CAGR) of 14%, increasing from 220 GW in 2011 to 823 GW in 2021, as reported by the International Renewable Energy Agency (IRENA) [1]-[3]. Learning innovative techniques for balancing electricity grids is essential for their efficient operation [4][5]. Among various renewable energy sources, wind energy production is rapidly increasing. The planet's installed wind capacity rose to 175 TWh in 2019–2020 and to 275 TWh in 2020–2021, respectively [6][7]. Figure 1 presents the estimated global onshore wind power generation for 2023 as 1.021 gigawatts. In 2024, China has the biggest generator of wind power with new capacity 116.6GW of 26% of top five market the statistic. determined by the power output by nation. To meet 18% of the world's energy demand by 2050, the International Energy Agency has made significant efforts [8][9]. Figure 2. shows the world offshore growth to 2030. To maintain consistent energy production yields during the offshore wind power peak, wind farm operators frequently benefit from high, steady wind speeds (10–20 m/s). The capacity curve is a graph that shows the range of wind speeds at which turbines produce their nominal power output. likewise have minimal impact on production when wind speed fluctuations fall within this region [10][11]. Wind energy is emerging as a viable economic solution to meet future electricity demand as fossil fuel power plants are phased out [12]-[15]. These two wind turbine technologies, doubly-fed induction generators (DFIG) and permanent magnet synchronous generators (PMSG), are connected through power converters. When power converters are operating at maximum capacity, the PMSG initially costs more than the DFIG, which has a gear-box mechanism and a 20–30% power converter rating. Numerous techniques are being used in the literature to regulate the independent DFIG and PMSG wind turbine control strategies [16]. For example, the DFIG wind

*Corresponding Author
Email: dawooddahiru@gmail.com

turbines [17] Fault Current Limiters (FCLs), power system stabilizer [18][19]. The integration of wind energy into the grid is hampered by several issues, such as unstable generation, issues with power quality active and reactive, and stability of the power system [20][21]. Power system stability is widely recognized as a critical issue for the safe functioning of systems, DC chopper, crowbar, and reactive power correction [22]-[24], to Maximum Power Point Tracking sliding mode control (MPPT) [25]. The power, frequency, or rotor speed are the inputs used by the damping controller [26]. The selection and proper tuning of damping and AVR controller parameters influence the extent of power system oscillation damping [27][28]. Design damping controllers may be created using a variety of types and schemes, including coordination damping control and PSS type and FACTS, which include elements of both schemes. Recent developments in artificial intelligence (ML) and the continued integration of energy from renewable sources (RESs) like wind energy into the electrical grid have led to the development of ML damper controller systems [29][30]. The frequency, voltage, magnitude, and angle of an infinite bus, or SMIB, are fixed. The infinite bus connection point can be used to symbolize the connection to a resilient grid, which absorbs the injected power without noticeably altering the voltage or frequency. In this review project, a complex network is used to introduce wind farms of DFIG and PMSG into the SMIB system [31]. This is the first review work on damping controller on SMIB integrated with wind farm of DFIG and PMSG. Some of the papers or journals of 2011 to date, are cited to adopt some relevant information. contribution to knowledge:

- Modelling and simulation of renewable energy (wind farm) with SMIB system.
- Design of damping controller and performance evaluation in a wind farm (DFIG and PMSG) integrated system.
- Eigenvalue analysis for obtaining best power system stability.

2. METHOD

This work focuses on developing a DFIG and PMSG (wind farm) integrated with a power grid (SMIB). The developing DFIG, PMSG, and SMIB systems consist of six generators: three double-fed induction generator, three permanent magnet synchronous generators connected completely to a single bus and the network which couples the complete model which make it 13 buses with generators and 12 buses of DFIG and PMSG. The complete system model incorporates numerous mathematical equations, damping controllers (PSS), system linearization, eigenvalue determination, objective functions and their types, and optimization techniques. Two major analyses are considered: dynamic rotor angle stability and damping controller. AI, PSS, and FACTs are also introduced. The formulation of optimization skills is discussed vividly.

2.1. WECS

The previous several decades have seen a growth in size and functions. A contemporary WECS consists of a wind turbine, a gearbox, an electric generator, and a power converter. The DFIG system offers a wide range of variable speeds through its reactive winding rotor, requiring constant maintenance to minimize mechanical failure risks [32], Conventional synchronous generators (SG) are grid-connected directly, however, to maximize wind energy output and grid integration, PMSG needs controllers and converters. Hence, a frequency converter, sometimes referred to as a grid-side or rotor-side converter, and a filtered through and linked to the PMSG before to sending the produced electricity to the grid. The grid-side converter facilitates the transfer active power produced to the power system grid network using the DC (direct current) connection voltage control pulse width modulation voltage source converter [33]. PMSG functioning is simultaneously managed by the rotor side converter. utilizing a voltage source converter with pulse width modulation or a rectifier. Since it is easier to develop onshore [34][35]. Given that the oceans and wind power account for more than 70% of the planet's surface and may provide large amounts of electricity when wind energy is absorbed above sea level, offshore wind farm integration may be regarded as a mutually beneficial arrangement [36][37]. Fundamental control mechanisms, such grid synchronization and voltage/current controllers, ensure that the power converters operate as intended and keep the grid's voltage and frequency stable. Moreover, fault ride-through and MPPT power restrictions are categories for certain control functions. The wind speed is divided into three regions: region one, region two, and region three. Region one is the area with modest wind speeds.

When the wind speed is lower than the nominal rate in region two, the torque control maximizes the power extracted from the wind [38][39], pitch controller maintains maximum power at region three [40]-[43]. one of the most powerful sustainable energy sources that may provide alternative energy security is wind energy, which has long been acknowledged. Numerous fields have seen an upsurge in research and development due to the remarkable surge in the utilization of wind turbine system [36]. The use of renewable energy sources like wind is growing, especially in nations where fossil fuels account for most of the electricity produced. Wind farms provide a practical use for wind power that extends to remote places. It should be link to the power grid, nevertheless, to maximize stability, sustainability, and flexibility. Depending on where they are, wind farms can be divided into offshore wind farms or onshore wind farms, which are located on land. Onshore wind farms are typically found in the vicinity of coastal areas or next to power grid installations on mountains; offshore wind farms are found deep within the ocean. Because of the consistent offshore wind farms in recent years, their installed capacity worldwide has been gradually growing [44]. The Devices that can harness the kinetic energy of winds include wind turbines. The turbine, which is connected to an electric generator, rotates by converting this kinetic energy into mechanical energy. The wind's kinetic energy may therefore be transformed into electrical energy, a source of energy that is useful. Wind turbines can be linked to the grid to power the utility grid, or they can be erected standalone to power isolated or distant areas it also expresses that increase in kinetic also wind speed increase [45][46]. Figure 3 and Figure 4 shows the wind energy conversion system of DFIG and PMSG.

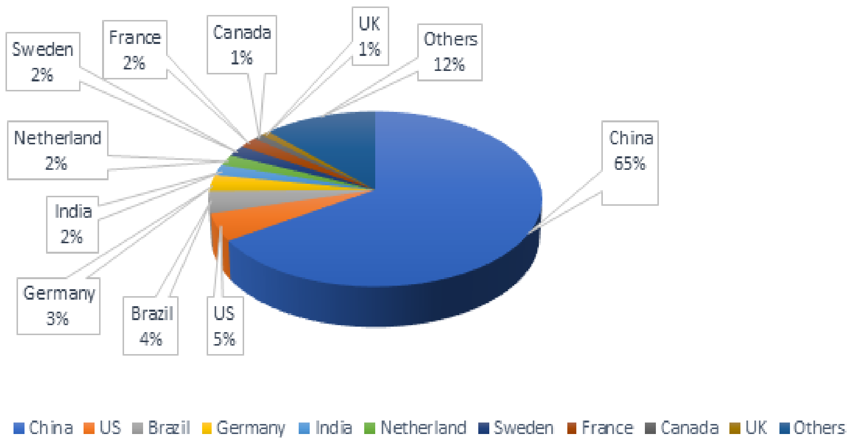

Figure 1. New installed onshore capacity of 2023 and share of top five markets (%)[47]

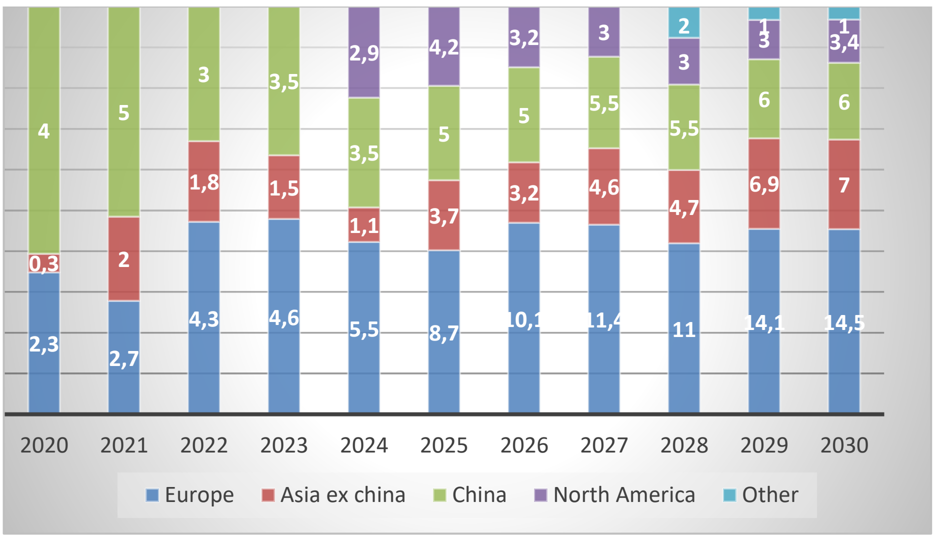

Figure 2. The world offshore wind capacity (GW) growth to 2030 [48]

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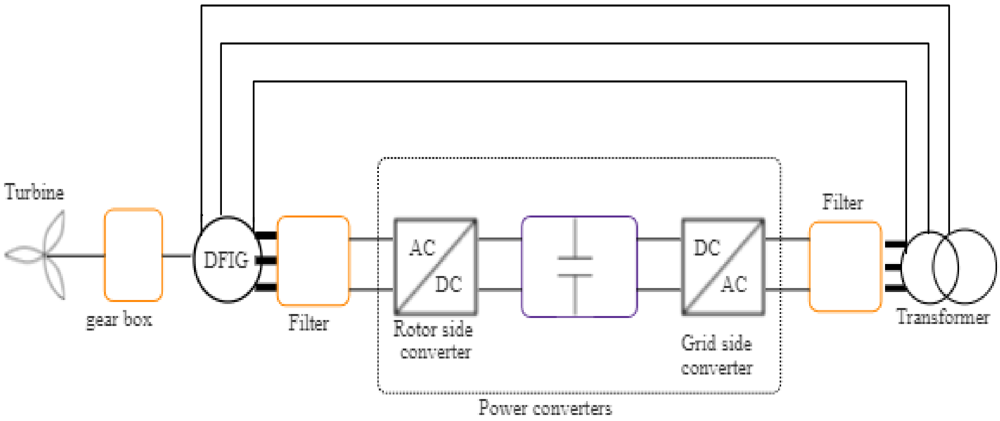

Figure 3. DIFG WECS

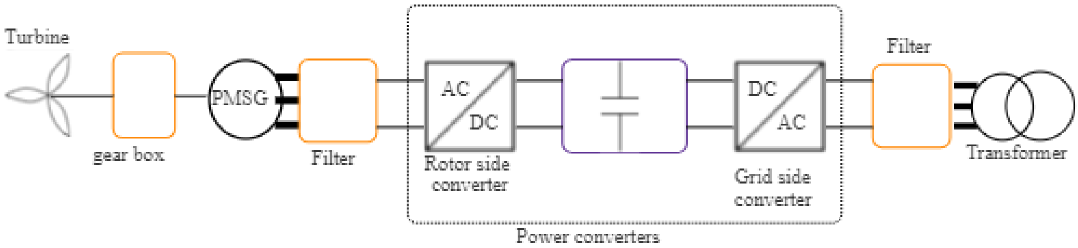

Figure 4. PMSG WECS

2.2. SMIB

Synchronous machines are modeled using Differential Algebra Equations for n number of machines representing grid synchronous machines, and their voltage regulators known as AVRs. This model is defined by Eq. (1) - (10). This can be seen in Figure 5.

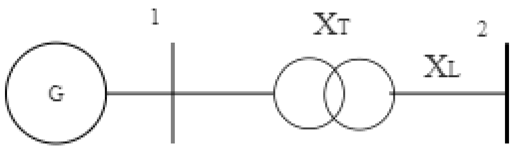

Figure 5. SMIB System [49][50]

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

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

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

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

$$T_{AI}\frac{dE'_{fdi}}{dt} = -K_{Ai}E_{fdi} + K_{Ai}(V_{refi} - V_i) \tag{5}$$

$$T_{EI} = E'_{di}I_{di} + E'_{di}I_{di} + (X_{qi} - X'_{qi})\, I_{di}I_{qi} \quad (6)$$

The electrical torque is developed from Eq. (4)

$$V_{di} = -R_{si}I_{di} + X'_{qi}I_{di} + E'_{di} \quad (7)$$

$$V_{qi} = -R_{si}I_{qi} + X'_{di}I_{qi} + E'_{qi} \quad (8)$$

All algebraic equations for the stators in the synchronous machines of a power system can be in matrix form equation.

$$V_d = -R_sI_d + X'_qI_d + E'_d \quad (9)$$

$$V_q = -R_sI_q + X'_dI_q + E'_q \quad (10)$$

The infinite bus test system simulates a stable grid connection when the injected power is absorbed at the infinite bus connection point with minimal impact on the system's voltage or frequency. This setup is particularly useful for modelling robust connections. The Single Machine Infinite Bus (SMIB) test system is a simplified model that includes only one synchronous generator. This machine consists of a stator with armature windings and field windings. There is a small air gap between the stator and the rotor, which is a critical component in the functioning of the generator. These two axes of symmetry correspond to the air gap and rotor shape, respectively, and are called the d- and q-axes. Time-varying fluxes between the armature and rotor circuits result in self and mutual inductances as the rotor rotates with respect to the stator. The synchronous machine model becomes more complex due to time-varying inductances [51][52].

2.3. WIND FARM

This is referred to as a combination of two or more turbines to form a power grid; the wind turbines may be either vertical or horizontal. In a wind farm, integrating a permanently magnet synchronous generator (PMSG) and a doubly fed induction generator (DFIG) has many benefits, such as improving efficiency, enhancing grid stability, reducing mechanical stress, increasing reliability, optimizing wind energy capture, and improving fault tolerance [53]. The proposed work is six generators using 3-DFIG and 3-PMSG to form wind fields as shown in Figure 6, Double Fed Induction Generators in Figure 3, and Permanent Magnetic Synchronous Generators in Figure 4 are usually used for the MW generation. Both active and reactive power are controllable and efficient in high power transfer but vary in terms of generator cost and maintenance.

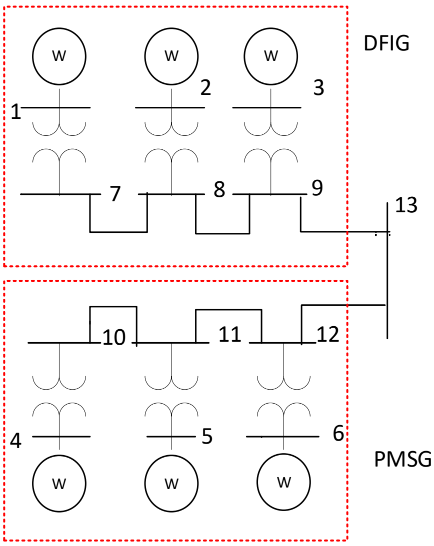

Figure 6. Wind farm [47]

2.4. POWER CONVERTER IN WIND ENERGY SYSTEM

Since the 1980s, power electronics have been more and more integrated into WTSs. Initially, a thyristor-based soft starter was used to link the wind turbine, then being ignored, and the generator was using the grid as a direct reference. The 1990s saw mostly using a diode bridge and a rotor resistance control. The last development was the back-to-back power converter, which started out with a lower power for doubly supplied induction. DFIG generator. With the increasing depletion of fossil fuels, the need to mitigate the effects of climate change, and the rising energy needs of developing nations, the number of renewable power generators linked to transmission and distribution grids through power electronic converters has increased exponentially. For example, it is anticipated that by 2030, the installed worldwide capacity of solar and wind power producers would generate around 3.8 TW of energy [54]. The technology of the DFIG is such that the Rotor Side Converter (RSC), or Machine Side Converter (MSC), and the Stator Side Converter (SSC), or Grid Side Converter (GSC) [55], are connected between the DC-link voltage for easy regulation of active and reactive power. To efficiently capture energy, this type of wind turbine functions throughout a broad. The use of several power converter topologies to synchronous generators (SGs), DFIGs, induction generators (IGs), and permanent magnet generators (PMGs) with control systems is discussed in [56][57]. The PMSG wind turbine boasts a completely rated back-to-back power converter, in contrast to the partially rated DFIG wind turbine technology. Consequently, this type of wind turbine is more likely to have the highest degree of flexibility and superior control over both actual and reactive power. But it's depressing how expensive the PMSG is at first [58][59]. A back-to-back capacitor converter can be connected to different voltages or frequencies within the wind farm; these enable grid functions like power compensation. It is made up of a dc link capacitor in addition to an MSC and GSC. To provide adequate energy convection and grid integration, grid-side converters function in conjunction with generator-side converters. A significant component of wind energy conversion, GSCs are designed to control bus voltage, current, and reactive power distribution continuously. They may also adjust frequency and voltage at the point of connection, known as grid integration. The grid side: Regardless of wind speed, the converter must adhere to grid codes [60]. This implies that it should be able to respond quickly to changes in active power and regulate the reactive power of the inductive and capacitive sources. Under typical operating conditions, the grid side's fundamental frequency and voltage amplitude should be almost constant, and the current's total harmonic distortion must be kept to a minimum degree. MSC provides the controllability and conversion of frequency from AC-DC and aids in torque and speed control by connecting the wind turbine generator to the grid [61]. The various wind energy converter technologies are categorized in the figure below, as studied in [62]-[64]. Table 1 and Figure 7 show the various types of WECs based on generators and power converter ratings.

Table 1. The difference between five various types of WECS configuration [64]

	Type 1	Type 2	Type 3	Type 4	Type 5
Generator used	SCIG	WRING	DFIG	SCIG, EESG And PMSG	EESG
Power converter utilization	No	Diode and chopper	AC-DC-AC or AC-AC	AC-DC-AC or AC-AC	No
Power converter rating	0%	10%	30%	100%	100%
Speed rating	Fixed speed ±1%	Semi variable speed ±10%	Semi variable speed requires ±30%	Full variable speed optional for EESG or PMSG 0-100%	Full variable speed required 0-100%
Gear box requirement	required	Required	Required	optional for EESG or PMSG	required
Soft stater	required	Not required	Not required	Not required	Not required
PF correction	required	Not required	Not required	Not required	Not required
MPPT ability	Impossible	Restricted	Achievable	Achievable	Achievable
Advantages	• High reliability • Low initial cost • Simple	• High efficiency • Low maintenance • Long life cycle	• High efficiency • Flexibility against system disturbances • Improved dynamics performance	• Smooth connection to grid • High efficiency • More robust against the fault	• Low cost and Area
Disadvantage	• Low efficiency • Direct effect on grid	• Hi energy loss in rotor resistance	• High cost • Required constant maintenance	• High cost • Large size • Complexity • High loss of power converter	• Mechanic-al problem of converter

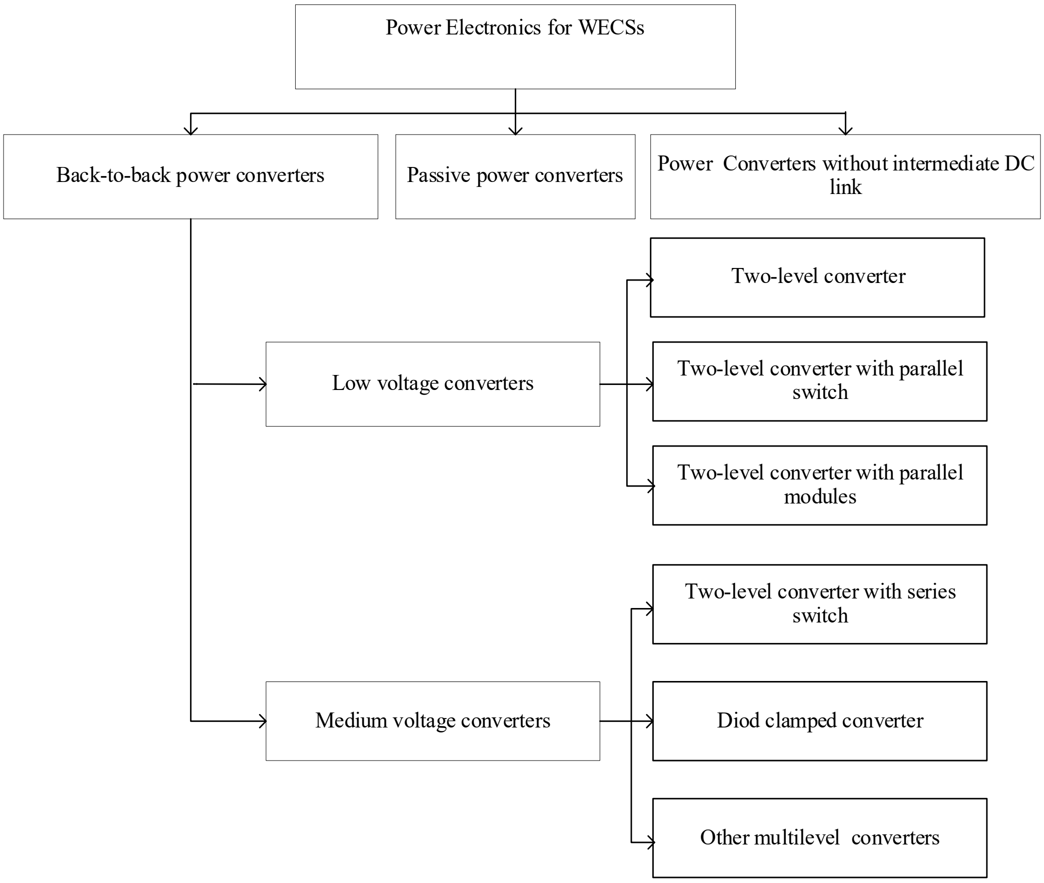

Figure 7. Power electronic converters classification for WECs [64]

2.5. WIND POWER

The cubic power of the velocity is the turbine power. The greatest power that may be theoretically extracted from the wind is provided by Betz's law. Greater extracted energy is correlated with greater wind speeds.

$$P_{out} = \frac{1}{2}A_s\rho^3 = \frac{1}{2}A_s\rho\left(\frac{v_a+v_b}{2}\right)(v_a - v_b) \tag{11}$$

$$P_{input} = \frac{1}{2}A_s {v_a}^3 \tag{12}$$

The turbine efficiency can be found as

$$\frac{P_{out}}{P_{input}} = \eta_t \tag{13}$$

The condition for a maximum efficiency can be found by setting $\frac{d\eta_t}{dt} = 0$

Which gives the maximum efficiency η_t to be $\eta_{t(max)} = 59.3$

2.5.1. Wind turbine model

The mechanical and torque power extracted from the wind turbine are given in Eq. (14)-(19)

$$P_T = \frac{1}{2}A_s\rho C_p(\lambda, \beta_p){v_w}^3 \tag{14}$$

$$C_p(\lambda, \beta_p) = 0.5176\left(\frac{119}{\lambda + 0.08\beta} - \frac{4.06}{1+\beta^3} - 0.44\beta\right)e^{\left(\frac{-21}{\lambda+0.08\beta} - \frac{0.735}{1+\beta^3}\right)} + 0.0068\lambda \tag{15}$$

$$\frac{d}{dt}\omega_g = \frac{1}{2H_g}(T_S - T_g) \tag{16}$$

$$T_s = K_{tg}\theta_{tg} + C_{tg}\frac{d}{dt}\theta_g \tag{17}$$

$$\frac{d}{dt}\theta_{tg} = \omega elB(\omega_t - \omega_s) \tag{18}$$

$$\frac{d}{dt}\omega_t = \frac{1}{2H_t}(T_t - T_s) \tag{19}$$

Where ρ is air density, V is wind speed, C_p is the power coefficient, C_{tg} is torque coefficient, A_s is swept area by blade, λ is tip speed ration.

2.6. WECS GENERATORS

The two main categories of electric machines used to produce wind power are synchronous and induction generators are categorized in diagrams under various types of generators in wind energy described in this study [65]-[75]. It can be seen in Figure 8.

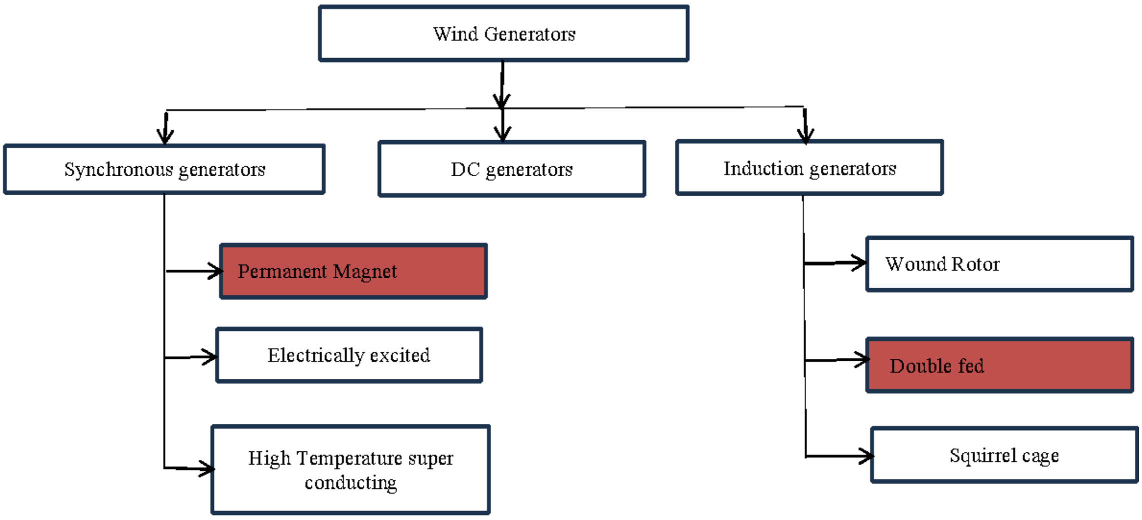

Figure 8. various wind turbine generators

2.6.1. Generator Model

The proposed generators are DFIG and PMSG. The model is described by the equation given below for the stationary and rotary parts of the generator. The generator (DFIG and PMSG) comprises two parts or sections: the stationary and rotary parts. The input voltage from the network to generate causes current to generate and the torque equations. Details of the notation can be seen in Table 2.

$$\frac{L'_s}{\omega elB}\frac{d}{dt}i_{sd} = -\omega_s L'_s i_{sq} - R_1 i_{sd} + \frac{e'_{sq}}{\omega_s T_r} + \frac{\omega_g e'_{sd}}{\omega_s} + v_{sd} + K_{mrr}v_{rd} \tag{20}$$

$$\frac{L'_s}{\omega elB}\frac{d}{dt}i_{sq} = -R_1 i_{sq} + \omega_s L'_s i_{sd} + \frac{\omega_g e'_{sq}}{\omega_s} - \frac{e'_{sd}}{\omega_s T_r} - v_{sq} + K_{mrr}v_{rq} \tag{21}$$

$$\frac{1}{\omega_s \omega elB}\frac{d}{dt}e'_{sd} = -R_2 i_{sq} - \left(1 - \frac{\omega_g}{\omega_s}\right)e'_{sq} - \frac{e'_{sd}}{\omega_s T_r} + K_{mrr}v_{rq} \tag{22}$$

$$\frac{1}{\omega_s \omega elB}\frac{d}{dt}e'_{sq} = R_2 i_{sd} - \frac{e'_{sd}}{\omega_s T_r} + \left(1 - \frac{\omega_g}{\omega_s}\right)e'_{sd} - K_{mrr}v_{rd} \tag{23}$$

$$i_{rq} = -\left(\frac{e'_{sd}}{X_m}\right) - K_{mrr} i_{sq} \tag{24}$$

$$i_{rd} = -\left(\frac{e'_{sq}}{X_m}\right) - K_{mrr} i_{sd} \tag{25}$$

Table 2. Mathematical symbols and meaning

i	i-th synchronous generator
T'_{do}	d-axis open-circuit time constants
T'_{qo}	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
ω_{elB}	Electrical base speed

2.7. STABILITY IN POWER SYSTEM TECHNOLOGY

Power systems need stability because it guarantees the grid's dependability and security [76]. According to the definition of power system stability, it is the system's capacity to recover from a physical disturbance and reach a state of operational equilibrium with the majority of its variables limited to ensure the system's overall integrity at a given starting operating condition [77].The grid impacts of CIGs have led to revisions and expansions to the stability categorization in Figure 9 [78]. This work focuses only on rotor angle stability.

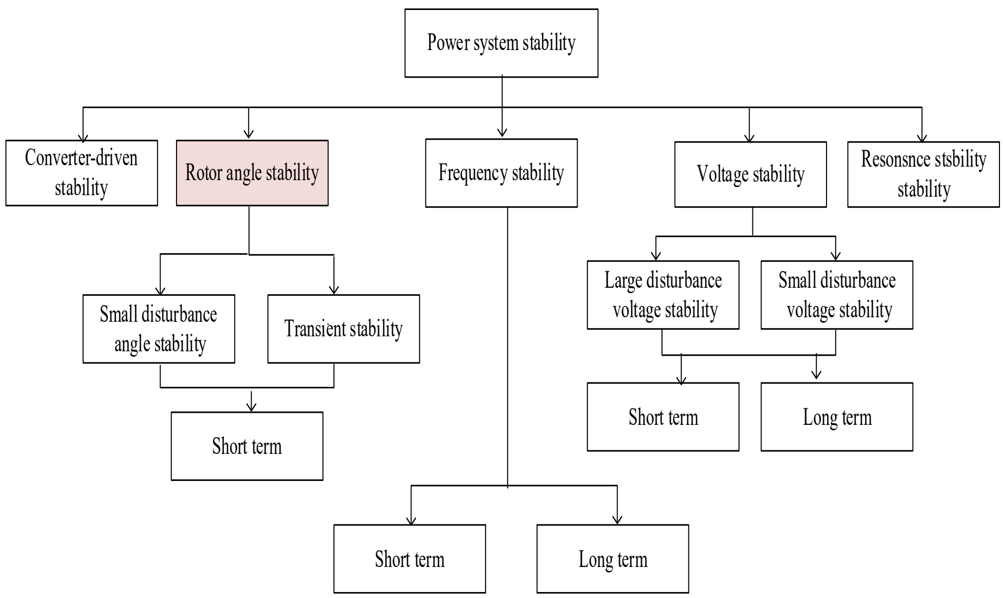

Figure 9. types of power system stability [69]

2.7.1. Oscillation in Power System

An intrinsic feature of synchronous generators is oscillations in the power system, which cause variations in output power while the rotors spin at synchronous speed. Oscillations in the power system are a fundamental characteristic of an integrated power grid system and are primarily caused by the non-linear nature of synchronous generators. Oscillations in the power network system, which happen as a sequence of connected incidents within a synchronous generator, can be caused by any incident or disturbance in the power system. Under typical operating circumstances, the physical and electromagnetic torque ratio keep the synchronous generator's rotor speed at synchronism. The rotor's speed changes, either increasing or decreasing from its synchronous speed this is known as swing equation, in response to any disturbance that throws off the balance [79]. If power system oscillations are not sufficiently muted, they may affect the stability of the whole power grid system and cause power outages for millions of people. Table 3 and Figure 10 show the current leading power system oscillation incident that leads to power outages.

Table 3. List of recent significant events involving power system oscillations that resulted in blackout

Year of incident	Date of incident	Country	Total number of people effected
2019 [80]	March,7	Venezuela	30
2019 [81]	June,16	Argentina, Paraguay, Uruguay	48
2019 [82]	August 4-5	Indonesia	100
2020 [83]	August 17	Sri Lankan	21
2021 [84]	January 9	Pakistan	200
2022 [85]	October 4	Bangladesh	140
2023 [86]	January 23	Pakistan	230

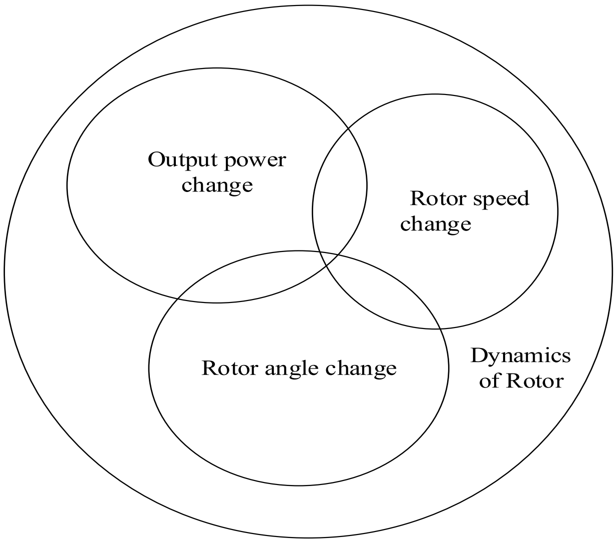

Figure 10. Dynamics of rotor angle

2.7.2. Rotor Angle Stability

Oscillations in the power grid, which happen as a sequence of connected events in a synchronous generator, can be caused by any incident or disturbance in the power system [87]. The rotor angle changes in responding to variations in speed based on power angle characteristics. The synchronous generator rotor speed is maintained at synchronous speed under normal operating circumstances by the equilibrium of the mechanical and electrical torques. When there is a disturbance in equilibrium, the rotor speed diverges from its synchronous speed. This behavior is best described by the swing equation, which is presented in the study. Fundamental analysis requires an understanding of the system's numerous oscillation modes [88]. Due to Wind Farm's integration with SMIB, which forms a grid (tie lines), electromechanical oscillation is likely to be complex. These oscillations, which originate from an imbalance in mechanical and electrical torque in synchronous generators, are known as electromechanical oscillations, and their typical frequency range is between 0.2 and 0.7 Hz [89]. Electromechanical modes of oscillations, which come in two varieties: local area modes and inter-area modes [90], are used to categorize power system oscillations study in [90][91].

2.8. DAMPING CONTROLLER

When it comes to the power infusion from renewable energy sources, load changes and power generation upset the equilibrium of a steady electrical power system. A big, networked power system must maintain stability while considering a machine's various rotor angles. By reducing low frequency oscillations, this equilibrium guarantees the stability of the energy system within an acceptable limit of the system's functioning. These oscillations with a low frequency are associated with a collection of electrical power production equipment or synchronous generators. Nonetheless, a machine's electrical torque is made up of two parts: the damping and synchronizing parts. By dampening low voltage, the damping component contributes significantly to the rotor angle stability of a power system study in [92]-[95]. To reduce oscillations and enhance and preserve a power system's angle stability, proper system modelling and damping controller mechanisms are necessary. Various techniques have been employed for damping, including PSS, coordination control, and flexible alternating current transmission systems (FACTS). To reduce necessary instability oscillations and enhance power system stability, the PSS lead lag controller works in tandem with the machine's excitation system to regulate the output power by providing an additional synchronizing torque that is in step with speed eccentricity, its multimachine design utilizing local measurements [96][97], Figure 11 demonstrates several damping systems together with the damping controllers for each scheme. The PSS damping control can be seen in Figure 12. The coordination control can be seen in Figure 13. Details of coordination control notation can be seen in Table 4.

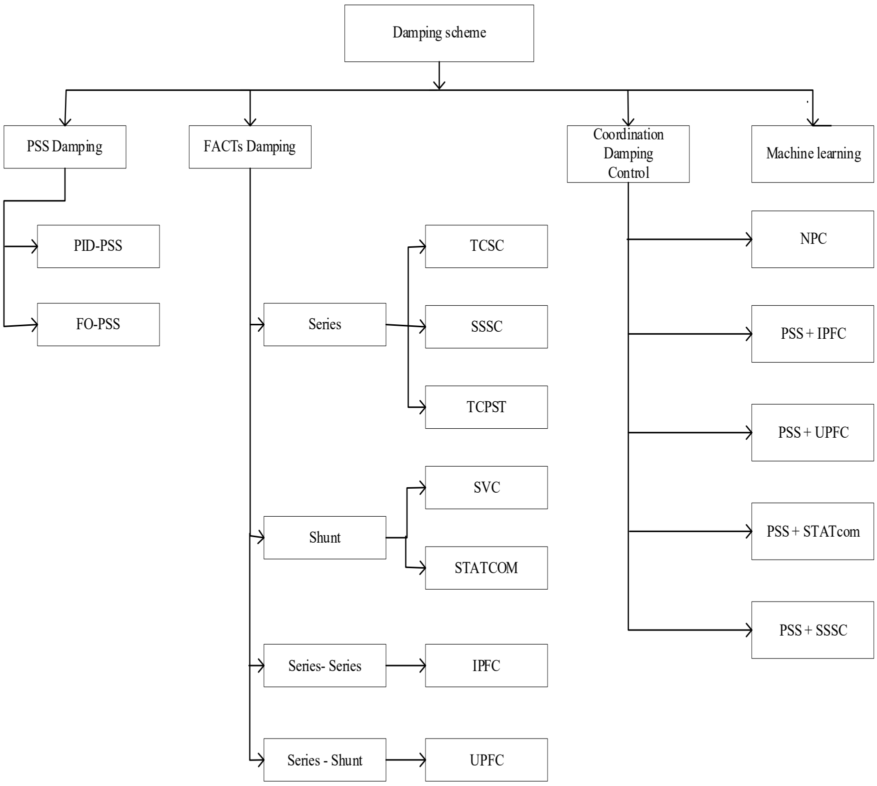

Figure 11. Damping scheme and controllers [93]

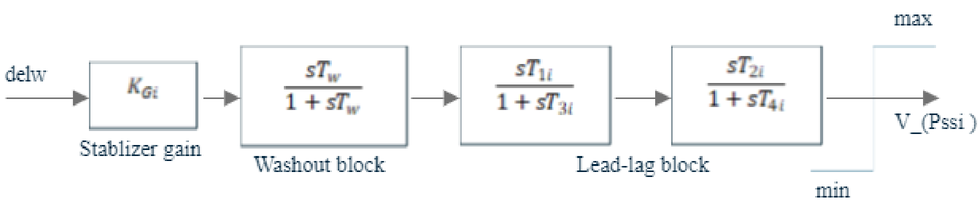

Figure 12. PSS Damping Controller [98]-[100]

Table 4: Abbreviations

TCSC	Thyristor controlled series capacitor
SSSC	Static synchronous series compensator
TCPST	Thyristor controlled phase shifting transformer
SVC	Static var compensator
STATCOM	static synchronous compensator
IPFC	Interline power flow controller
UPFC	Unified power flow controller
NFC	Near Field Communication
PSS	Power system stabilizer
SSSC	static synchronous series compensator
PID	proportional integral derivative
POD	power oscillation damper

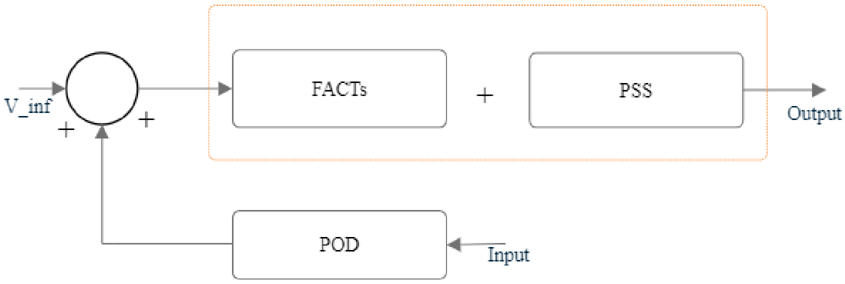

Figure 13. Coordination between damping controller and FACTs

2.8.1. Power System Stabilizer

As a significant and cost-effective damping technique, for power system stability, PSS was initially proposed in 1969. In accordance with the synchronous machine principle, the excitation voltage may be adjusted to change the output power produced. By installing PSS, an extra input signal is provided to the synchronous generator's excitation system. In response to the phase-locking speed variation, PSS applies an additional synchronizing torque. Thus, increasing oscillations are attenuated and system stability is limited. When appropriately built, PSS can reduce both inter-area and local electromechanical forms of oscillation. For efficient damping, PSS coordination can also be used in conjunction with other classical controllers, such as proportional integral derivatives (PID). PID-PSS, for instance, was created on SMIB. The lead-lag power system stabilizer is the most often used damping controller. It is linked via the exhaust system to increase the mechanical oscillation factor. Also, it serves to improve the dynamic stability of the grid or power supply [101][102]. It is usually mounted on huge synchronous generators that provide the grid with electricity [103].

2.8.2. FACTs

The power system community and practitioners are well aware of the advantages of Flexible AC Transmission System (FACTS) devices in improving the steady-state and dynamic capabilities of power systems [104]-[106]. 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 [107]. Long transmission lines are needed to integrate renewable energy sources, such as offshore wind farms, into the grid. An interconnected power grid system has extremely complicated oscillation dynamics as a result. The low frequencies of inter-area oscillation, which fall within the band of 0.8-3.0 Hz, are difficult to suppress with PSS implementation alone. Based on how they connect to the transmission line, FACTS devices are often categorized in [108][109].

2.8.3. Coordinate Damping Controller

When PSS and FACTS are combined, different controllers work together to effectively dampen different electromechanical oscillation modes. However, improper coordination or combination of these controllers can negatively affect power system damping over certain electromechanical modes and even cause the system to crash. Studies have been conducted where PSS and FACTS coordination was done. To coordinate the design of PSS and SVC study in [110], PSS-UPFC in [111], PSS-IPFC coordination damping controller [93].

2.9. Machine Learning

Artificial intelligence (AI) methods like neural networks and fuzzy systems have been proposed for single machine infinite bus (SMIB) systems; these approaches have recently been extended to include multi-machine power systems [112]. PSSs controllers based on artificial intelligence (AI) have become a popular research topic in recent years. These intelligent controllers have the capacity to learn from the environment in which they are used to enhance their performance. The literatures have suggested Fuzzy Logic PSSs (FLPSSs), which can be type-1 fuzzy (T1FLS), type-2 fuzzy (T2FLS), or adaptive fuzzy sliding mode PSS, Neural Network PSSs (NNPSSs), Adaptive Neuro-Fuzzy Inference System PSSs (ANFIS-PSSs) [102], stabilizer that uses a Neuro-Fuzzy Controller (NFC) to manage low frequency oscillations in power systems. NFC stabilizers have better qualities than FACTS stabilizers and can replace the job of PSSs [113]. A system's unknown model, such as the dynamics of manipulative robots or sensor transduction behavior, must be empirically approximated to use machine learning techniques. The word is widely relevant to various optimization approaches and other data-driven methodologies, even though neural networks are commonly utilized in this method to approximate functions [114].

2.10. SYSTEM LINEARIZATION

Examining the damping controller design process is particularly aided by the power system stability analysis. It is necessary to simulate the dynamic characteristics of the power system to conduct a stability analysis. The dynamic model of this power system makes use of differential, linear, and nonlinear equations (ODE), The linear time-invariant (LTI) state space model is known by this name. The Development of the LTI State Space Model involves linearizing nonlinear ODEs around an operational point to a system of first-order linear differential equations. Power system simulation is accelerated by linearization, which also helps to verify local stability and comprehend power system dynamics. For linear controller design, MATLAB®/SIMULINK® offers toolboxes like Rogers' power system toolbox (PST), Mat Dyn,PSAT [115]-[117]. The dynamics of a power system may be represented by a nonlinear ODE as follows in Eq. (26) and (27).

$$\dot{x}(t) = f\big((t), u(t)\big) \tag{26}$$

$$y(t) = g\big((t), u(t)\big) \tag{27}$$

$$x_o = f\,(x_o, u_o) \tag{28}$$

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{29}$$

$$y(t) = C(x) + Du(t) \tag{30}$$

The system states at equilibrium and the input vectors can be expressed in Eq. (28). After a slight divergence from the equilibrium of the system and an expansion around the balance and input vectors using Taylor's series, the state space solution of a linear system may be expressed as follows in Eq. (29) and (30). Where f and g are nonlinear functions, y is output vector, u is input vector and $x$is the state vector where A, B, C and D are state, input, output and feedforward matrices.

2.10.1. Integral Time-Base Error

The variance between the generator's rotor speed and its nominal value is the definition of error in the damping controller's time-based error function [117]. The following are the definitions of the objective functions: integral square time square error (ISTSE), integral square error (ISE), integral absolute error (IAE), integral square error (ITAE), and integral square error (ITSE) [118][119]. The best system is the one with the lowest index, and the index value must always be either positive or zero. The goal function is to reduce (ITAE, ITSE, IAE, ISE, or ISTSE).

$$ISE = \int_0^t \quad (\Delta\omega_i)^2\, dt \tag{30}$$

$$ISTSE = \int_0^t \quad (t|\Delta\omega_i|)^2\, dt \tag{31}$$

.

Subjected to

$$K_{imin} \leq K_i \leq K_{imax} \tag{32}$$

$$T_{imin} \leq T_i \leq T_{imax} \tag{33}$$

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

2.10.2. Eigen Value

The location of the eigenvalues in a linear system on the s-plane used to evaluate the stability of the system is represented in the following Eq. (34).

$$(\lambda_i = \sigma_i \pm j\omega_i) \tag{34}$$

Where $\lambda_i = eig(A)$ is the real part, $\sigma_i = real(\lambda_i)$ is the imaginary part of the eigen value on s-plane. A is the state matrix of the linearized model. The stability criteria for an eigenvalue are shown in Figure 14. The major advantage of optimization algorithms in developing damping controller is shifting the eigen values to the left side of the s-plane. If any of the eigenvalues are on right side of the s-plane, then the system is not stable. The system is stable if all the eigenvalues are on the left side of the s-plane.

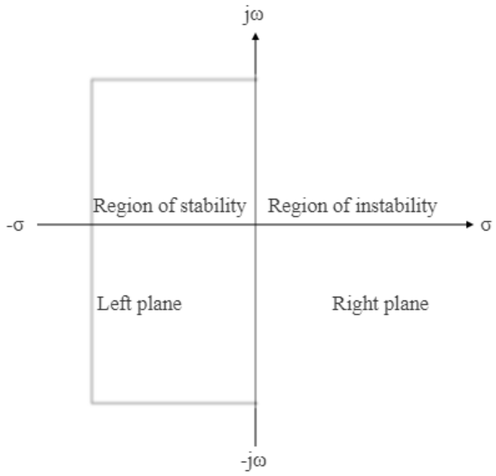

Figure 14. Stability criteria for system eigenvalues

2.11. OBJECTIVE FUNCTION

It is necessary to apply objective functions with various formulations while designing robust damping controllers. Reducing the rotor speed deviation error by employing different integral error functions is the aim of the integral time error-based function. Either a positive or zero index value should be present, and the system with the smallest index should be considered the best. The primary focus of the objective function in eigenvalue analysis is moving the eigenvalues to the left side of the s-plane. The two basic classifications used to define the objective function are single objective function and multiple objective function. As a result, the damping factors and ratios, the real and imaginary components of eigenvalues, represent these objective functions. For a function to be optimized for its sole purpose, that is, to determine the rate at which the oscillation amplitude decreases. The damping ratio is an essential component. The function's performance can be improved by adjusting the damping ratio, which can greatly minimize oscillations. Damping factor and damping ratio

$$\sigma_i = real(\lambda_i) \tag{35}$$

$$\zeta_i = -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \tag{36}$$

2.11.1. Singular Objective Function

For a function to be optimized for its sole purpose, the damping ratio, on the other hand, plays a crucial role in preventing oscillations from going beyond their natural limits, which eventually enhances the damping efficacy of operators. The lowest damping ratio, thus, has been ascertained and subsequently optimized by the optimization of control parameters [94] that is, to determine the rate at which the oscillation amplitude decreases. The damp ratio is an essential component. The function performance can be improved by adjusting the damping ratio, which can significantly minimize the oscillation [120]-[124]. The pace at which oscillation amplitude decays is determined by the damping ratio. Thus, by optimizing the controller settings, the damping ratio was optimized for quicker oscillation abatement [125][126], On the other hand, rather than relying just on one mode, system damping is dependent on the operation of the dominating electromechanical modes. Consequently, a single-objective function called the complete damping index that considers dominant modes study in [127][128].

2.11.2. Multi objective Function

In the formulation, the multi-objective function seeks to accomplish two or more goals [129]. The damping factor's improvement is linked to the improvement in oscillations' overshoot. In contrast, however, the damping ratio lengthens the oscillations' settling period. Thus, the damping ratio and damping factors play a role in achieving strong damping in the system's functioning. Typically, the damping ratio and damping factor are mentioned. for multi-objective systems. The formulation required to locate eigen values in a D-shaped area is widely used in multi-objective techniques. Various techniques have been used to create a stability region in the shape of a *D*. In [130]-[132] Numerous studies on damping controller optimization in earlier literature have recognized the importance of multi-objective functions [133].

2.12. OPTIMIZATION TECHNIQUES

For damping systems, the controller parameters have been optimized using a variety of optimization approaches during the past few decades. There are four general categories into which optimization techniques may be divided: conventional, deterministic, heuristic, and hybrid strategies. The next sections cover these optimization techniques' uses as well as their benefits and drawbacks [134][135].

2.12.1. Conventional

The notion of classical control theory serves as the foundation for the controller parameter optimizations in the frequency domain. This kind of methodology comprises Bode plots, gain margin methods, phase, and root locus techniques. Numerous reports of traditional optimization approaches being used to tune the damping have been made in the last few decades in charge [136][137]. The control system might not be able to meet the requirements effectively anymore. To circumvent this problem, contemporary control theory-based methods are introduced in [138]-[141].

2.12.2. Deterministic

Mathematical programming that properly forecasts future behavior based on previous data behavior is known as deterministic approaches. To arrive at a global optimal solution, deterministic approaches make use of the problem's analytical features. PSS optimization has been approached using deterministic techniques like linear programming. The best damping performance was obtained by using gradient-based sequential quadratic programming. Deter mistic vital select initial point [142][143].

2.12.3. Hybrid Strategies

Various methods have been suggested to optimize damping controllers. The primary objective of employing several methodologies is to attain resilient damping in the face of power system fluctuations. Even though each approach has its benefits and drawbacks, hybrid strategies have been used to get better performance. Over the years, many hybrid techniques have been claimed to yield better robust performances. By merging the BFOA and PSO approaches, the hybrid PSO-BF strategy was created. PSS optimization, coordination damping of PSS, and SVC controller optimization were all effectively achieved with the use of BF-PSO [144][145]. Recently, a new hybrid method based on local and global research principles was presented to improve the damping [146].

2.12.4. HEURISTIC

Heuristic optimization methods are a type of global optimization that find the answer by applying the stochastic (randomization) approach. An algorithm or collection of guidelines that discovers a solution or learns by trial and error is called a heuristic approach. We refer to these enhanced heuristic methods as metaheuristic algorithms. The ideas that were inspired by nature served as the foundation for most heuristic algorithms. The heuristic algorithm's advantage is that, unlike deterministic approaches, it does not necessitate guessing the initial answer. This kind of optimization is more adaptable and effective than deterministic methods for resilient optimization. When addressing a range of optimization issues, such as nonlinear, non-differentiable complicated problems, heuristic approaches hold up well when contrasted with conventional and deterministic optimization methodologies. Metaheuristic algorithms are categorized as evolutionary-based, swarm-based, physics-based, human-based, and game-based.

2.12.4.1. Evolutionary Based

Random operators like crossover, mutation, and selection, as well as ideas from natural selection theory and biology, have been used to create evolutionary-based metaheuristic algorithms. One of the most well-known metaheuristic algorithms is the Genetic Algorithm (GA), which draws inspiration from natural selection, Darwin's theory of evolution, the process of reproduction, and biological concepts [147]. Another evolutionary computation is called differential evolution (DE), which employs a differential operator in addition to the ideas of biology, random operators, and natural selection to produce novel solutions [148].

2.12.4.2. Physics-Based

The ideas, laws, forces, phenomena, and theories of physics have served as the basis for physics-based metaheuristic optimization. Enameling metals is the primary source of inspiration for one of the most well-known physics-based techniques, called Simulated Annealing (SA). An object in a heat bath is subjected to a steady temperature increase until the object melts during this physical procedure. Physical separation or random placement of the solid particles is used. As the temperature drops from such a high energy level, the thermal bath gradually cools, allowing the particles to arrange themselves into a regular crystal lattice composition [149]. Inspired by the modelling of Newton's laws of motion among masses contained in a system and his law of universal gravitation, the Gravitational Search Algorithm (GSA) is a physics-based computing technique. The Multi-Verse Optimizer (MVO) was designed with inspiration from the three notions of a black hole, white hole, and wormhole found in cosmology research. Water Cycle Algorithm (WCA), Spring Search Algorithm (SSA), Atom Search Optimization (ASO), Momentum Search Algorithm (MSA), Quantum-inspired Metaheuristic Algorithm, and Nuclear Reaction Optimization (NRO) are a few more physics-based techniques [150]-[156].

2.12.4.3. Human-Based

Algorithms known as human-based metaheuristics have been created with inspiration from social interactions, human behavior, and relationships. As the most popular human-based metaheuristic algorithm, Teaching Learning Based Optimization (TLBO) gets its major inspiration from student-teacher and student interactions within the educational environment. The primary concept behind the creation of Poor and affluent Optimization (PRO) was the efforts of two social classes, the affluent and the poor, to better their financial circumstances [157], some of the algorithms such as Archery Algorithm (AA), War Strategy Optimization (WSO), Chef Based Optimization Algorithm (CBOA), Team work optimization, Brain Storm Optimization (BSO are discus in [158]-[163].

2.12.4.4. Game-Base

To simulate the rules of different individual and group games and to mimic the actions of players, referees, coaches, and other effective interactions, game-based metaheuristic algorithms have been proposed. The Tug-of-War Optimization (TWO) algorithm was primarily inspired by the notion of player competitiveness inside the confines of the tug-of-war game [164] Premier Volleyball League (PVL) algorithm is introduced based on mathematical modelling of player interactions, competitions, coaching instructions during game [165] and Football Game Based Optimization (FGBO) [166].

2.12.4.5. Swarm-Base

Models of swarming phenomena, natural events, and the behaviors of animals, birds, insects, and other living things have been used to construct swarm-based metaheuristic algorithms. Within the optimization fields, Particle Swarm Optimization (PSO) was one of the first metaheuristic algorithms to be presented and was widely employed. Fish and birds use to find food sources as a primary source of inspiration when creating PSO [167][168]. Ant Colony Optimization (ACO) is a swarm-based method inspired by the ability and strategy of an ant colony to identify the shortest path between the colony to food source [169]. Grey Wolf Optimization (GWO) is an algorithmic metaheuristic that draws inspiration from the social behavior and hierarchical structure of grey wolves while hunting [170]. Inspired by ocean and sea predator tactics and its Levy combat maneuvers to catch victims, the Marine Predator Algorithm (MPA) was created [171]. The Tunicate Swarm Algorithm (TSA) was primarily inspired by the tunicate's approach and search mechanism when it came to hunting and locating food sources [171]. Some other swarm-based methods are White Shark Optimizer (WSO) [172], Reptile Search Algorithm (RSA) [173], Raccoon Optimization Algorithm (ROA) [174], African

Vultures Optimization Algorithm (AVOA) [175], Farmland Fertility Algorithm (FFA) [176], Slime Mold algorithm (SMA) [177], Mountain Gazelle Optimizer (MGO) [178], Sparrow Search Algorithm (SSA) [179], Whale Optimization Algorithm (WOA) [180], Artificial Gorilla Troops Optimizer (GTO) [181], Pelican Optimization Algorithm (POA) [182], Bermuda Triangle Optimizer (BTO) [183] and Secretary bird optimization algorithm (SBOA) [184].

3. PROPOSE METAHEURISTIC ALGORITHMS

The suggested Secretary Bird Optimization Algorithm (SBOA) is explained, and a mathematical model of the Secretary Bird's behavior is created for solving engineering problems. Secretary Birds' hunting techniques and their actions when dodging predators are regarded as sophisticated behaviors that provide new insights into optimization and problem-solving. These observations could serve as the foundation for the creation of optimization algorithms. Consequently, a potential optimization technique for resolving engineering optimization issues is suggested in this study, which draws inspiration from the Secretary Bird's hunting strategy and predator avoidance behavior [184].

3.1. SBOA inspiration and behavior

The Secretary Bird, scientifically known as Sagittarius serpentarius, is a remarkable African raptor that stands out for both its unusual look and habits. It is extensively found in Africa's grasslands, savannas, and open riverine regions that are south of the Sahara Desert. In addition to semi-desert locations and forested areas with wide clearings, secretary birds are commonly found in tropical open grasslands, savannas with few trees, and open places with long grass. Secretary bird plumage is distinguished by grey-brown feathers on the wings and back, pristine white on the breast, and deep black on the belly. Famous for its distinct hunting technique, the Secretary Bird is distinguished by its long, strong legs and talons that allow it to sprint and hunt on the ground. It generally walks or trots across grasslands, adopting the demeanor of a "secretary at work" by bending its head and carefully examining the ground to find food concealed in the grass. Insects, reptiles, small mammals, and other animals are secretary birds' main sources of food. They quickly dash their prey and use their strong talons to grasp it once they detect it. After that, they hit the victim with the ground, killing and devouring it. Secretary Birds, with their exceptional intelligence and keen eyes, are a strong enemy of snakes. They can anticipate snake movements, causing them to become weaker. The Secretary Bird's constant taunting and leaping above the snake make it a formidable opponent, ensuring its survival. The Secretary Bird's hunting behavior, as shown in Figure 2, is closely linked to the Secretary Bird Optimization Algorithm (SBOA). The bird's initial hunting behavior corresponds to SBOA's startup stage, with subsequent stages aligning with the Secretary Bird's hunting procedure. It employs C1 and C2 mechanisms against predators.

3.3.1. Initial preparation

The Secretary Bird Optimization Algorithm (SBOA) technique utilizes the population-based metaheuristic approach to determine the values of decision variables based on the position of each Bird in the search space. This approach aims to identify potential fixes to current issues.

$$X_{ij} = lb_j + r \times (ub_j - lb_j), i = 1,2,\dots,N, j = 1,2,\dots,Dim \tag{36}$$

Where ub_j and lb_j are lower and upper bound secretary bird, and r denote the random number from 0-1. The Secretary Bird Optimization Algorithm (SBOA) employs a population-based methodology, Whereby optimization begins from a pool of potential solutions, as demonstrated by Eq. (37). Within the upper and lower bound restrictions for the given issue, these potential solutions X are created at random. Every iteration treats the best answer found so far as about the ideal option.

$$X = [x_{1,1}\ x_{1,2} \cdots x_{1,j} \cdots x_{1,Dim}\ x_{2,1}\ x_{2,2} \cdots x_{2,j} \cdots x_{2,Dim} \vdots \vdots \ddots \vdots \ddots \vdots\ x_{i,1}\ x_{i,2} \dots x_{i,j} \dots x_{i,Dim} \vdots \vdots \ddots \vdots \ddots \vdots\ x_{N,1}\ x_{N,2} \dots x_{N,j} \dots x_{N,Dim}]_{N \times Dim} \tag{37}$$

Where N is the secretary bird number. Every secretary bird stands for a potential fix to improve the issue. The values that each secretary bird suggests for the problem variables may thus be used to assess the objective function. Next, a vector is created by compiling the values of the resultant objective function using Eq. (38).

$$F = [F_1 \vdots F_i \vdots F_N]_{N\times 1} = [F(X_1) \vdots F(X_i) \vdots F(X_N)]_{N\times 1} \tag{38}$$

(38)

.

Where F is the vector objective function values and F_i represent the objective function collect from i^{th}. The objective function plays a crucial role in solving minimization problems, where the secretary bird with the lowest objective function value is the best candidate solution, while in maximization problems, the secretary bird with the highest objective function value is the best candidate solution. The SBOA members have been updated using two different natural behaviors shown by the secretary bird. These two categories of actions include the following: (i) the secretary bird's hunting strategy; and (ii) its escape technique. Therefore, every member of the secretary bird colony is updated in two distinct stages throughout each cycle. The secretary bird's hunting process is classified into three equal time intervals based on biological statistics of its stages and the duration of each phase. These are as follows:

$$t < \frac{1}{3}T, \quad \frac{1}{3}T < t < \frac{2}{3}T, \quad \frac{2}{3}T < t < T$$

Representing the three stages of the secretary bird's feeding cycle: finding prey, eating prey, and attacking prey. Consequently, every process in sboa is modeled. Updating the secretary position during searching can be modeled mathematically are summarized in Table 5.

Table 5: Updating Secretary bird position during hunting

Exploration phase	Time duration for each phase	$x_{i,j}^{new\ P1}$
Searching for prey	$t < \frac{1}{3}T$	$x_{ij} + (x_{random\_1} - x_{random\_2}) \times R_1$
Consuming prey	$\frac{1}{3}T < t < \frac{2}{3}T$	$x_{best} + e^{(\frac{t}{T})^4} \times (RB - 0.5) \times (x_{best} - x_{ij})$
Attacking prey	$\frac{2}{3}T < t < T$	$x_{best} + \left(1 - \frac{t}{T}\right)^{\frac{2t}{T}} \times x_{ij} \times RL$

Where t denotes as the current iteration, T is the max and present iteration number, $x_i^{new\ P1}$ is the update state of i^{th}. x_{random_1} and x_{random_2} are the random candidate in first iteration. All the phases are in the same position X_i of secretary bird i^{th}, R_1 is random generation of array 1 by D from range [0,1], Dim is dimension of solution space, $x_i^{new\ P1}$ is the value of j dimension, and $F_i^{new,P1}$ is the fitness value of objective function

$$X_i = \{X_i^{new,P1}, if\ F_i^{new,P1 < F_i}\ X_i, else \tag{39}$$

We apply the weighted Levy combat, often known as RL

$$RL = 0.5 \times Levy(Dim) \tag{40}$$

The Levy combat distribution function is denoted by Levy (Dim). The calculation is as follows: and a fixed constant of 0.01

$$Levy(D) = s \times \frac{u \times \sigma}{|v|^{\frac{1}{\eta}}} \tag{41}$$

Also η is a 1.5 fixed constant. Two random integers in the interval [0, 1] are u and v. The σ is define as

$$\sigma = \left(\frac{\gamma(1+\eta) \times sin\left(\frac{\pi\eta}{2}\right)}{\gamma\left(\frac{1+\eta}{2}\right) \times 2\eta\left(\frac{1-\eta}{2}\right)} \right)^{\frac{1}{\eta}} \tag{42}$$

$$\sigma = \left(\frac{\gamma(1+\eta) \times sin\left(\frac{\pi\eta}{2}\right)}{\gamma\left(\frac{1+\eta}{2}\right) \times 2\eta\left(\frac{1-\eta}{2}\right)} \right)^{\frac{1}{\eta}} \tag{43}$$

4. CONCULUSION AND RECOMMENDATION

Instability becomes a major challenge in power systems, consequently collapse of the power grid. Wind energy and its converter technology are introduced. Every day power converters lead in changing and improving renewable energy systems. Damping controllers are designed to keep the rotor angle in a synchronous condition. Many techniques are introduced to dampen oscillations such as PSS plus facts. In developing double-fed induction generators and permanent magnet synchronous generators integrated with single-machine infinite bus system. Damping controllers are developed purposely to maintain and stabilize the stability of the power grid Various schemes regarding damping controllers are discussed, such as PSS, FACTS, coordinate, and machine learning damping controllers. In this review, enhancing the performance of damping oscillations. Optimization techniques come into consideration for obtaining the best objective function. The integral time best error provides highly effective control to enhance power system stability. Suggestion: Damping controllers like machine learning (ML) need to be taken into consideration for the following reasons: Real time operation, Improved accuracy, Handling non-linearity and Flexibility

ACKNOWLEDGEMENTS

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

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BIOGRAPHIES OF AUTHORS

Engr. Dr. Sabo Aliyu (Ph.D.) MIEEE. PES. (Member, IEEE) completed his bachelor's degree in electrical engineering from the Prestigious Ahmadu Bello University, Zaria, Kaduna State, Nigeria in 2011. Engr. Dr. Sabo Aliyu completed his M.Sc. and Ph.D. Degrees in Electrical Power Systems Engineering from the University of Putra Malaysia. His main research areas include the application of Neuro Fuzzy Controllers to power systems, Computational Intelligence techniques, Power System Oscillation Damping Controller Designs, Power Systems Optimizations, Power Flow and Optimal Power Flow, Power Quality, and Robust controllers with several online publications. Engr. Dr. Sabo Aliyu is currently a Senior Lecturer at the Nigerian Defence Academy, Kaduna State, Nigeria. He is a registered Engineer under the Council for the Regulation of Engineering in Nigeria (COREN). He can be contacted at email: saboaliyu98@gmail.com.

Dahiru Dauda M. Eng (in view) Nigeria Defense Academy date started (September 2023) option Power and machine Engineering in the Department of Electrical and Electronics Engineering. Attended Abubakar Tafawa Balewa University Bauchi in 2021. Department of Electrical and Electronics Engineering. Graduate Member Nigeria society of Engineers (NSE), Student member IEEE, Student member (IAENG). student trainee at Jos Electricity Distribution company (JED) (2018,2022-2023). Six-month Industrial trainee at TCN, Jos (2019). three-month graduate trainee with Taihe Electromechanical Engineering company at Gombe state Dadinkowa hydropower plant 40MW (2023) email: Dauda.dahiru2022@nda.edu.ng.

Noor Izzri Abdul Wahab graduated from the University Of Manchester Institute Of Science and Technology (UMIST), UK, in Electrical and Electronic Engineering in 1998, received his MSc in Electrical Power Engineering from the Universiti Putra Malaysia (UPM) in 2002 and his PhD in Electrical, Electronic and System Engineering from Universiti Kebangsaan Malaysia (UKM) in 2010. He is an Associate Professor at the Department of Electrical and Electronic Engineering, Faculty of Engineering, UPM. He is a Researcher and the founding member of the Centre for Advanced Power and Energy Research (CAPER), UPM and an associate member of the Centre of Electromagnetic and Lightning Protection Research (CELP), UPM. He is a registered Chartered Engineer under the Engineering Council UK and the Institution of Engineering and Technology (IET) UK, a professional engineer (Ir.) awarded by the Board of Engineers Malaysia (BEM), a member of The Institution of Engineers Malaysia (IEM), an IEEE senior member, a member of the IEEE Power and Energy Society (IEEE-PES), a member of the IEEE Computational Intelligence Society (IEEE-CIS), a member of the Institution of Engineering and Technology (IET) UK, a member of the International Rough Set Society (IRSS). His areas of interest include power system stability studies (Dynamic and Control), application of artificial intelligence in power systems and power system quality.