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Improvement of an AC microgrid system's stability by using a fuzzy logic-based PSS controller

A. Arora* • M. Bhadu

Electrical Engineering Department, Engineering College Bikaner, Rajasthan, India

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Abstract: This research article presents the low-frequency oscillation damping control of an AC Microgrid. It is integrated with four distributed generation units in which two DGs are renewable energy source based solar PV and wind energy using DFIG and the other two DGs are conventional synchronous generator-based hydro and diesel generators. There is insufficient generation through renewable-based DG then a diesel generator is employed as an emergency unit to fulfil the requirements and maintain and control the deviation of the frequency of the system. The use of renewable-based DG affected the system's dynamic stability and the characteristics of an integrated microgrid differ from conventional sources of generation. This investigation explores the impression of the deployment of multiple forms of the power oscillation damping (POD) controllers to distributed generation sources of grid forming AC Microgrid. The main various types of POD controllers are conventional lead-lag PSSs, MBPSS-4B, and proposed robust fuzzy logic PSS (FLPSS) controllers are implemented on distributed generation units of AC Microgrid for the elimination of low-frequency oscillation. Low oscillation frequencies between 0.1 and 2 Hz are the focus of this work. The system's damping ratios and stability margins because of MG integration are observed using eigenvalues analysis. The results of the simulation test demonstrate the accomplishment of the robust fuzzy logic PSS controller regarding conventional lead-lag PSSs and the MBPSS-4B controller during circumstances of fault.

Keywords: AC Microgrid, DFIG, fuzzy logic controller, power oscillation damping controller, renewable energy sources, solar PV

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*Corresponding author.
E-mail address: amitarora8505@gmail.com(A. Arora).

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1. Introduction

The modern conventional power grid should be equipped with enough resources to supply the electricity needed by consumers. On the other hand, substantial grid imbalances in the utility grid can lead to instability and even extensive network blackouts. The system frequency is one of these stability challenges. To maintain the stability of the system, the frequency must be within its approved limit. The predetermined frequency range has been maintained in a conventional power grid using conventional controllers. This controller assists in keeping the frequency at its standard level (Abbasi et al., 2023). The operating costs associated with installing these conventional generators are unacceptable for system operators. The electricity grid faced major modifications as distributed solutions eventually substituted conventional synchronous generators. To continuously increase industrialization and urbanization, the load demand rapidly increases every day. To meet the load demand and imply less stress on the conventional utility grid through the utilization of RESs. The generation of electricity from the RESs maintains stable operation in peak load conditions and protects against the blackout of the energy generation system. Renewable energy sources including solar, biogas, and hydro are developing at the strongest rates all over the world (Fazal et al., 2023). The major advantages of distributed generation are both economical and environmentally friendly. As an illustration, this energy cost is a premium, limitless, and clean resource which can reduce carbon emissions. Unfortunately, the integration of the electricity grid into the distributed generation is difficult, because it cannot be dispatched and is greatly affected by the weather (Siti et al., 2022). On the other side, generation through RES’s like solar and wind are unpredictable due to weather dependency. This unpredicted behavior of RES’s causes the deviation in the system frequency. If the generation of renewable energy sources is not stabilized quickly, then the deviation in frequency continuously increases and reaches beyond the operating range. So, the researchers of the power system provide a direct technical approach to overcome the frequency deviation and stabilize the power fluctuations caused by the RESs penetration into the traditional power system (Ismail et al., 2022).

1.1. Background

Research on RESs is heavily promoted to meet the ever-increasing demand for energy and the diminishing fossil fuel resources, even though the most advantageous RESs, such as solar and wind, are highly climate-dependent and the energy produced using the generation of power just one source with existing technology is insufficient to meet customer demands. To improve reliability, built microgrids with more distributed generators and energy storage devices. Future power demand might be met by connecting such microgrids, which comprise regionally available waste bioenergy, together with solar and wind-based renewable power systems (Hou et al., 2018).

The demand increased from the generation, the electrical power storage devices such as battery storage systems, ultra-capacitor storage systems, and flywheel storage systems that store excess energy from RESs and provide it to the main grid to maintain the overload demand conditions. Therefore, the energy storage system maintains stable operation when there is a deviation in frequency and power fluctuations. As a microgrid is interlinked to the primary external electrical network, electromechanical low-frequency oscillations resulting from unpredictable perturbations and unexpected renewable penetration are increased. The microgrid's stability concerning dynamic damping is determined by an alteration in network inertia, which is heavily influenced by the microgrid's low compounded physical inertia (Jain & Saxena et al., 2023). Small signal stability is defined as the regaining stable behavior when it is subjected to small unpredicted uncertainties or disturbances. The system is influenced by the unpredicted uncertainties which affect the system-damping performance. Power oscillations regards the low-frequency oscillations cause the instability of the system and affect the stability of the modern power system. Dampening the power oscillations or LFO should be improved by the robust design of the power oscillation damping controller. The deviation in the system frequency caused by the unpredicted disturbance in the power system may introduce the rotor speed deviation and rotor angle deviation in the synchronous distributed generators of the power system. This deviation in the rotor of the distributed generators is the main reason for the instability of the system. The deviation in the rotor was improved by the different robust design damping controllers (Alnuman et al., 2022).

1.2. The problem

Within the microgrid, conventional and non-conventional distributed generators are linked to the main primary conventional power grid utilizing a power electronics controllers’ interface, allowing them to function as needed while also maintaining the system’s quality and stability. The microgrid's stability is necessary for ensuring the stable performance or operation of all DGs, along with the primary electrical system performed in a synchronized way, as well as stabilizing signals whenever there are fluctuations in the voltage and frequency signaling (Rafique et al., 2022). In the generation from the wind technology, double-fed induction generator-based wind turbines (DFIG-WT) are employed at variable speeds to extract maximum renewable energy from the wind to take advantage of their favorable characteristics, which include reduced noise, lower converter power, enhanced efficiency of the power, and lower power losses. The low-frequency oscillations are affected by microgrids which need to be explored because they pose a huge problem for system stability (Puchalapalli et al., 2020). The dynamics of the synchronous machine of power systems are changed by the utilization of the DFIG wind energy conversion system. This influence on dynamic stability is analyzed through eigenvalues which show that there are both positive and negative consequences as DFIG penetration increases. The different operating modes of DFIG are investigated through a damping controller. As earlier mentioned, research suggested that damping modes of inter-area are highly impacted by wind generation penetration giving unsatisfactory damping performance (Kumar et al., 2022). On the other hand, with the most effective utilization of the renewable power generation source solar photovoltaic system, the resulting amount of electrical energy is increased through the alteration of solar radiation. The phenomenon known as photovoltaic is utilized to derive electrical power from solar cells. The dynamic stability affected by the influence of the generation of PV solar is analyzed which shows that it has both beneficial and harmful consequences of the stability regarding the geological place and penetration degree of PV solar (Zhao et al., 2023). The disturbance in the existence of PV solar affects the operating conditions which influence the system's dynamic stability. The system in terms of dynamic behavior gets highly affected by PV solar penetration and by some other parameters such as disturbance and geo-location of PV solar generation system. The foremost concern is to explore the system in terms of dynamic behavior with the influence of penetration of PV solar under the state of disturbance and loading conditions (Nikolaev et al., 2021).

Recently, some studies to create more sophisticated dynamic control techniques for PV-wind-battery-based microgrids have been described. There is a lot of investigation to improve or increase the dynamic stability of microgrids by designing a different robust control strategy or controller and controlling the voltage magnitude of each microgrid's common bus with the help of different types of drop controller techniques (Satapathy et al., 2017). Despite all the work that has gone into microgrid control, there isn't a solution in the literature of dynamic instability brought about due to the low-frequency oscillations with microgrid penetration. Implementing a robust low-frequency damping controller for electromechanical oscillation characteristics of a microgrid penetration power system is crucial or necessary in this situation (Arora et al., 2023a). By applying sufficient rotor torque of the synchronous machines, the power system stabilizer integrated into several power systems strengthens the damping of electromechanical oscillation of low frequency. A phase-compensation method that contributes an adequate phase lead that makes up for such phase lag between both the excitation and the electric torque is an essential component of a conventional PSS (Arora et al., 2023b). Numerous efforts using different PSS modification strategies have been described in the literature within the research for an effective PSS for the modern power system. It involves (i) applying meta-heuristic algorithms and artificial intelligence techniques for PSS parameter selection (ii) integrating different control strategies during PSS design, and (iii) enhancing CPSS performance through structural adjustments. Since all these PSSs can only provide phase compensation of narrow band within a specific desired value, they cannot operate as intended for the precise system characteristics for which they were designed (Kumar & Bhadu, 2022). Considering the, it is of utmost importance to establish an adaptable, effective and robust PSS that can successfully operate according to a wide range of circumstances for operation and power system functional unexpected outcomes. An additional investigation needs to be conducted to assess the effectiveness of every power system stabilizer in systems within the framework of combined generation instead of penetration of the microgrid. To improve the operational efficiency of synchronous generators, many forms of PSS have been implemented, which are categorized as standard PSS relying on power and speed input dependent, multiband PSS, fuzzy logic power system stabilizer (FLPSS), robust $H\infty$, etc. PSS is an exceedingly powerful preventive technology for undamped oscillatory modes in the modern power system (Xie et al., 2019).

PID controller-based PSSs are primarily included in studies on structural reforms in PSSs. With its three distinct modes of operation, a PID controller may provide impressive robust control performance with an extensive range of power system operational parameters, Moreover, frequent and unforeseen dynamic changes may occur in a real power system, which could result in an abrupt shift in the system's operating conditions. However, it is necessary to add new functions to a PID controller to make it more effective (Lakshmi et al., 2020).

Due to their capacity to improve the performance and resilience of closed-loop systems, fractional calculus-based controllers have recently inspired a huge amount of awareness from both academia and industry. Recently, researchers have investigated how to develop fractional-order controllers with computational intelligence. An implementation of fractional order-based controllers is found in different areas of power systems, including oscillation damping control in renewable energy-based DGs, LFC, AVR, and WADC, describes how to design a multiband PSS (MBPSS) of fractional order for multi-machine power systems that need to dampen inter-area oscillations (Arora et al., 2023c).

For the low-frequency oscillation damping control of the microgrid penetrated in conventional electrical systems, a fractional order type fuzzy logic PSS (FLPSS) control strategy is given in this study. To diminish the difficulties of extensive computation and imperfect modeling of dynamic power systems, PSSs utilizing fuzzy logic have been presented. The dynamic stability range of modern power systems is increased by this hybridization of fuzzy logic with PID-based PSS. However, when compared to traditional PID-based PSSs, such strategies offer enhanced damping effectiveness (Kerdphol et al., 2019).

A brief discussion of the literature survey gives the conclusion to apply the upcoming technical approach for designing robust conventional lead-lag controllers. There is also a further need for attentiveness to enhance the damping of low-frequency oscillations in the AC Microgrid system with the execution of the different lead-lag types and robust proposed fuzzy logic power oscillation damping controller.

1.3. AC Microgrid power system with low frequency oscillation

When a power system is subjected to a small perturbation or uncertainty, its capability to retain stability is referred to as "small signal stability." Due to inadequate synchronizing and damping torques, instability conditions that may develop include rotor oscillation or a steady rise in the generator's rotor angle. Local modes of oscillation are those connected with a single generator, whereas inter-area modes of oscillation are those that involve a group of synchronous generators. The oscillation frequencies of local and inter-area modes fall between 0.7 to 2 Hz and 0.1 and 0.8 Hz, respectively. Additionally, an increase in oscillation amplitude may cause a partial or complete shutdown of the electrical supply (Arora et al., 2023a).

To examine how the critical modes perform in terms of small signal stability and time domain responsiveness to small perturbations, eigenvalues analysis is used. Additionally, complex eigenvalues reveal the modes' frequency oscillation (f) and damping ratio (ζ_i), which are expressed by Equation (1).

$$\lambda_i = \sigma_i \pm j\omega_i \tag{1}$$

$$f = \frac{\omega_i}{2\pi} \tag{2}$$

$$\varsigma_i = -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \tag{3}$$

When every eigenvalue has a negative real portion, the system is said to be stable. This is consistent with the oscillatory modes' damped condition. The relationship between crucial eigenvalues and system state variables is investigated using sensitivity and participation factor analysis (PFA). This analysis offers details of the Participation among state variables and modes that are independent of the units and scale attached to state variables. More important state variables to the modes are indicated by higher participation factor values. The i^{th} and j^{th} modes of the state variables' participation factor (P_{ij}) are provided by Equation (4).

$$\mathrm{P}_{ij} = \phi_{ij}\psi_{ij} \tag{4}$$

Where ϕ_{ij} is the element on the right eigenvector and ψ_{ij} is the element on the left eigenvector (Kumar & Bhadu, 2022).

1.4. The proposed solution

This article examines the dynamic performance of the grid-connected AC Microgrid. Implementing power oscillation damping controllers improves small signal stability, especially LFOs. The effectiveness of the different controllers is examined and compared under the disturbance in the system. The proposed robust design fuzzy logic power system stabilizer (FLPSS) offers the best dynamic damping of low-frequency oscillations compared to other applied PSS in systems.

There are the following objectives of the research article.

- To enhance the dynamic damping performance in terms of low-frequency oscillations (LFOs) of the grid connected AC Microgrid using the technique of the power oscillation damping controllers.
- The effective execution of the various continuous mode power oscillation damping controllers such as conventional lead-lag, IEEE standard multiband PSS (MBPSS-4B), and fuzzy logic PSS (FLPSS) have been analyzed and compared.
- The overall effectiveness of the investigated controllers demonstrates that fuzzy logic PSS (FLPSS) is the strongest and most robust power oscillation damping controller that can enhance stability and dampen the LFOs of the AC Microgrid.
- Verify the recommended robust power oscillation damping controllers in the MATLAB/Simulink platform.

The remaining research paper part is distributed as an act under Section II, which presents an extensive design representation and technique for the AC Microgrid framework development., and Section III presents a description of controlling the AC Microgrid using different tuned variable conventional lead-lag PSS type POD controllers, MBPSS-4B POD controller, and designing robust fuzzy logic PSS type POD Controller. Section IV analyses the controller's functionality by demonstrating the simulation outcomes. Section V contains the conclusion, and the end is followed by references.

2. Test system of the AC microgrid

The test system of the AC Microgrid is represented in Figure 1. A Total of 24.5 MW of four power generating units, in which two units are conventional synchronous generators such as hydro, and diesel, and the rest two units are renewable energy sources such as DFIG, and solar PV are integrated into the conventional power grid rated with base 1000 MVA, 20 kV, and 50 Hz (Arora et al., 2023b). The present research analyses how renewable energy-based microgrid penetration affects the stability and control of an AC Microgrid system under different operational situations.

The primary goal of the study is to examine the power oscillation of the grid connected AC Microgrid. This investigation focuses on LFOs in an amount of 0.1-2 Hz since the objective of this examination is how to improve LFOs dampening of the system.

2.1. Modeling of the DFIG-based wind energy system

Figure 2 demonstrates a wind energy transformation technique implementing DFIG-WT. The generated electric energy can be expressed in Equation 5.

$$p_{mech.} = \frac{1}{2} C_p\left(\beta,\lambda\right)\pi R^2 \rho v_{wind}^3 \tag{5}$$

The resulting torque caused by the wind passing over the blades of the turbine is expressed by

$$T_m = 0.5\frac{C_P\left(\beta,\lambda\right)}{\lambda}\rho\pi R^2 V^3{}_{wind} \tag{6}$$

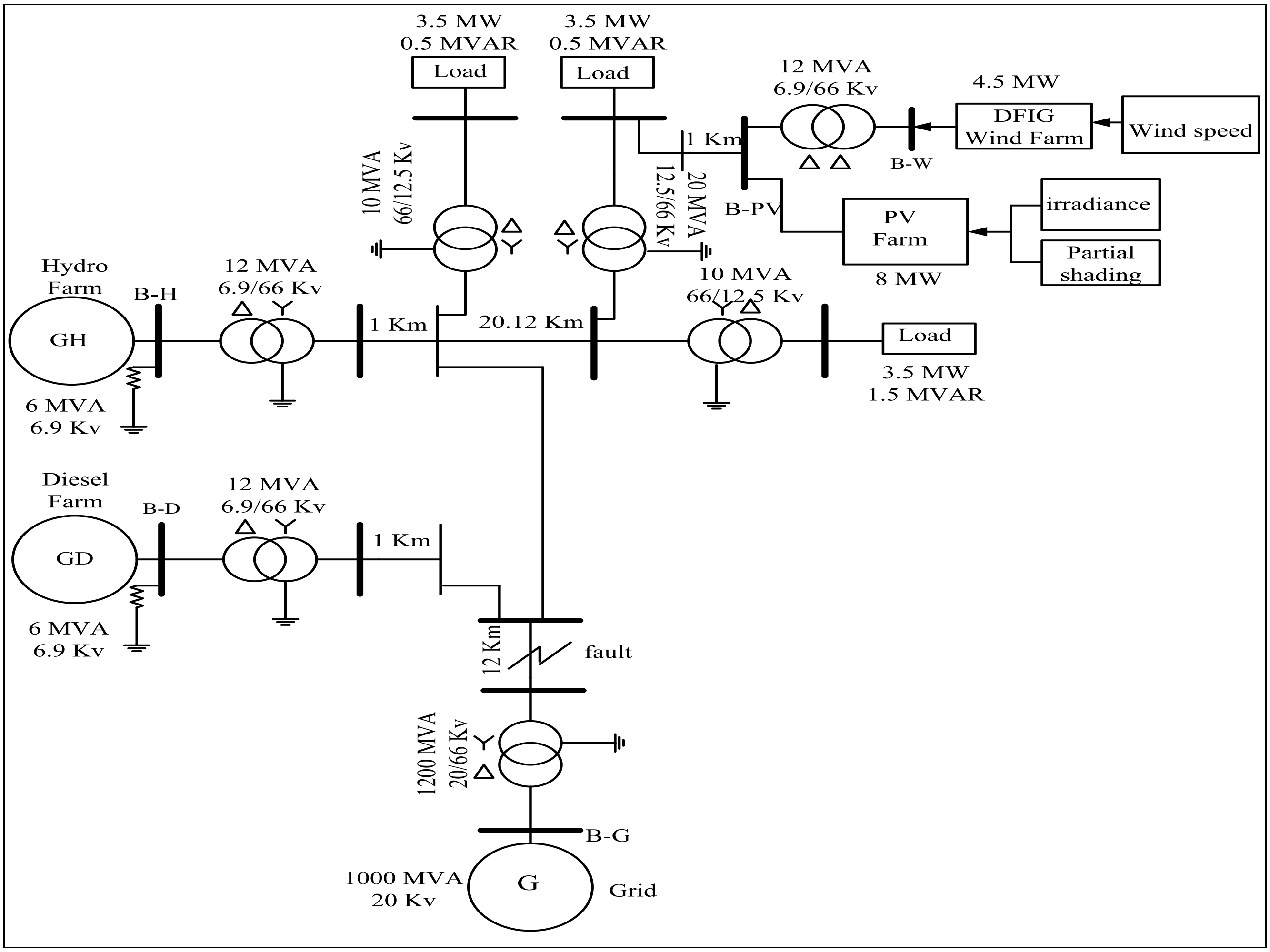

Figure 1. A grid connected AC Microgrid test system is illustrated in a single line diagram (Arora et al., 2023b).

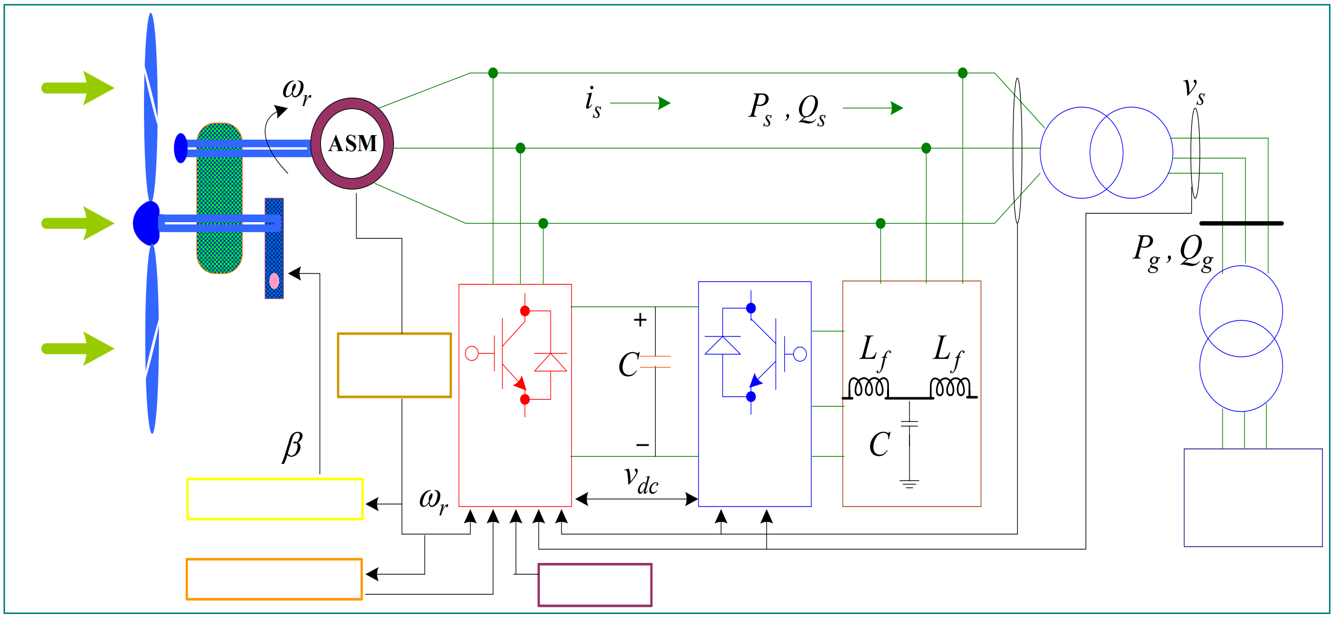

Figure 2. DFIG wind power generation with control scheme model.

where the value of the power coefficient $C_p(\beta,\lambda)$ corresponds with the pitch angle (β) and constant velocity of the turbine blade tip (λ), ρ expressing the density of air (Kg/m^3), v_{wind} and characterizing wind velocity $(m/\sec.)$, and the R defines turbine blade radius (m) (Nahak & Satapathy, 2021).

$$C_P\ (\beta,\lambda) = 0.5\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)\exp\left(-\frac{21}{\lambda_i}\right) + 0.0068\lambda \tag{7}$$

Equation (8) determines the tip speed ratio (λ_i).

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{8}$$

2.2. Modeling of solar photovoltaic cell

The generation of power through the solar photovoltaic system with grid-connected mode continuously increasing in modern power systems. The intermittent and uncertainty in the power generated through the solar photovoltaic plant may negatively influence the stability of the modern power system. Therefore, there is an increase in instability of low-frequency oscillations in the systems.

The solar photovoltaic (SPV) output current is illustrated by expression (9). Figure 3 depicts the manufacturing processes of a solar photovoltaic (SPV) farm arrangement using a control technique. Its solar PV system comprises a PN diode, current source, and resistor that occurs in (Hamid et al., 2022). The solar photovoltaic (SPV) grasps the solar power through solar irradiance converts it into electrical power and generates energy transfer through the inverter, which maintains the barrier between the solar photovoltaic and the main power grid and maintains reactive power control or voltage at the PCC.

$$I_{SPV} = N_{pc} I_{pc} - N_{pc} I_{rsc} \times \left[\exp\left(\left\{\frac{q}{F_c k T_s}\right\}\left\{\frac{V_P V}{N_s c} + I_{SPV} R_s\right\}\right)\right] \tag{9}$$

$$I_{pc} = \left(I_{scc} + k_{tc}\left\{T_s - T_{ref}\right\}\right) \times \frac{S_{rr}}{1000} \tag{10}$$

$$I_{rsc} = I_{T_{ref}}\left(\frac{T_s}{T_{ref}}\right)\exp\left(\left\{\frac{qE_{bg}}{kF_c}\right\} \times \left\{\frac{1}{T_{ref}} - \frac{1}{T_s}\right\}\right) \tag{11}$$

Where N_{pc} is the number of parallel cells, N_{sc} number of series cells, I_{pc} is the photocurrent, I_{rsc} is the reserve saturation current, F_c is the identity constant, T_s is the surface temperature, I_{scc} is the short circuit current, K_{tc} is the temperature coefficient of the short circuit current, T_{ref} is the reference temperature, S_{rr} is the solar radiation range, $I_{T_{ref}}$ is the reverse saturation current at a reference temperature, k is the Boltzmann constant, q is the charge of an electron.

2.3. Modeling of diesel engine generator

The electricity generation from solar PV and wind systems is weather-dependent and variable in nature. Therefore, the solar PV and wind system output is totally uncontrolled due to varies solar PV irradiance and the speed of the wind. Generally, the diesel generator is incorporated with the microgrid of renewable energy resources to supply continuous power to the consumers of the remote area. The structural representation of the diesel generator is illustrated in Figure 4, and the transfer function of each component is illustrated in Figure 5. The diesel engine is constructed with functional components such as a droop control system with droop R, actuator valve, and diesel engine blocks. $\Delta U_{\deg}$ is the transmitted control signal, ΔF is frequency deviation, ΔX_{gen} is valve rise location, $\Delta P_{\deg}$ and is diesel generator incremental deviation (Wilches-Bemal et al., 2022).

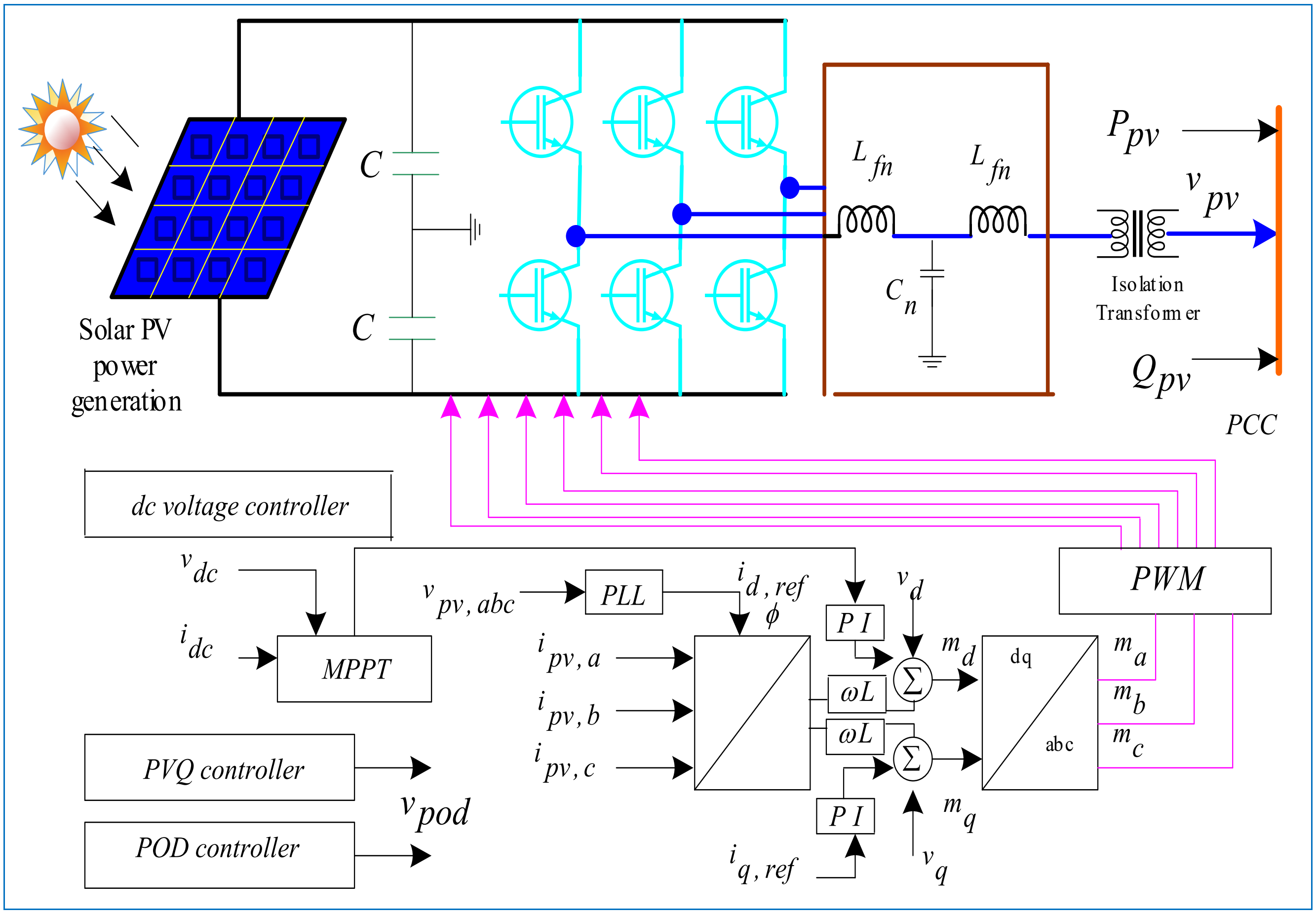

Figure 3. Solar photovoltaic (SPV) power generation with control scheme model.

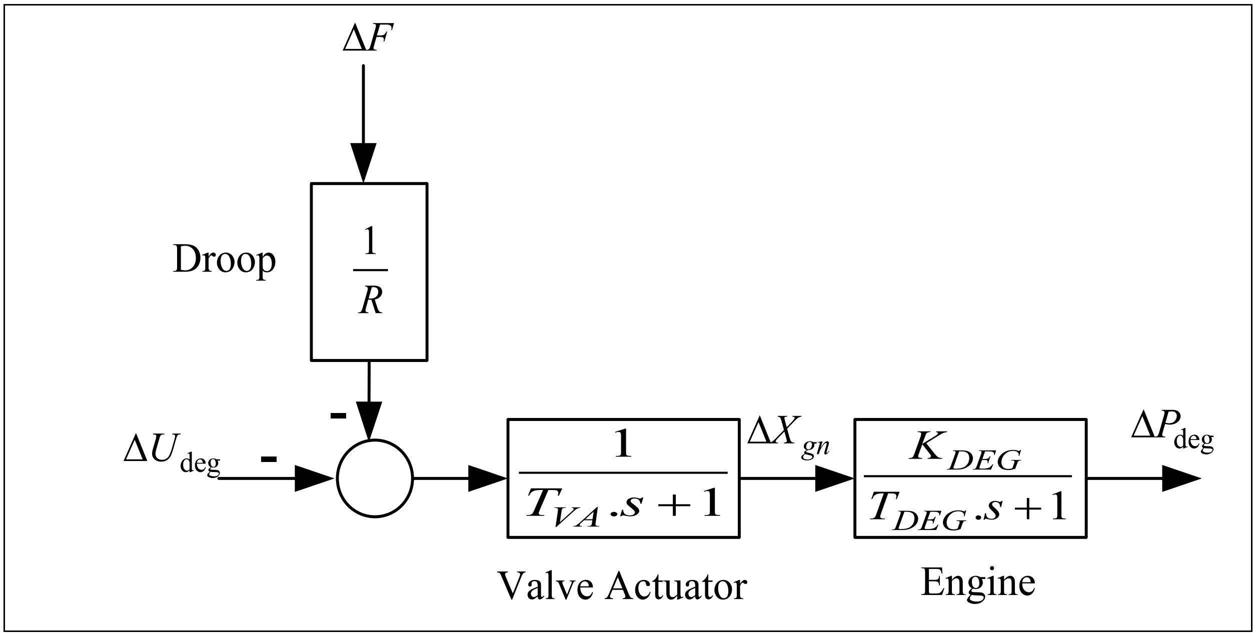

Figure 4. Block diagram function of the diesel generator

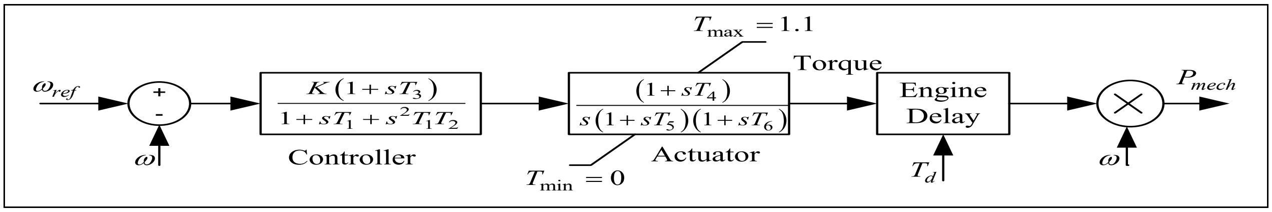

Figure 5. Transfer function blocks of diesel generator governor model.

2.4. Modeling of hydropower generator

The hydro turbine corresponds to the generator that transforms mechanical energy into electrical energy. Hydropower generating stations comprise a reservoir, a gate to release water to the generating station, and a canal is utilized to carry water from the reservoir towards the hydro turbine. The governor and turbine system are observed separately regarding the planning system of the hydropower system represented in Figure 6. The transfer function of the hydro governor consists of a single zero and two poles and the turbine transfer function consists of a single zero and single pole of the hydro generator are represented in Figure 7 (Satapathy et al., 2021).

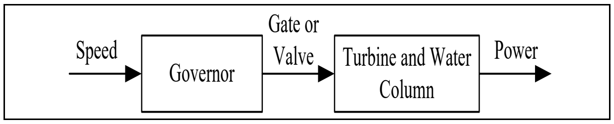

Figure 6. Basic hydro generator block diagram of governor turbine.

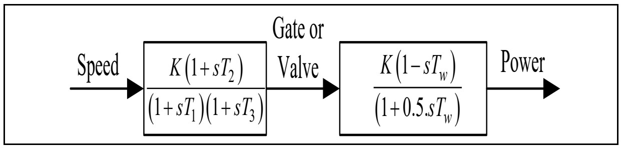

Figure 7. General hydro turbine model with transfer function.

3. Power oscillation damping (POD) controllers

The influence of the power oscillation damping (POD) controllers in systems is used to enhance the small signal stability and damp the power oscillations. The system is impacted by different unpredicted perturbations that affect the stability constraints corresponding to the parameters are deviations in voltage, frequency, rotor speed and angle, and output power. Considering the conception of an acceptable robust damping controller, the microgrid's stability needs to be enhanced, as well as the system should be able to withstand disturbances. FLPSS controller is used for controlled functioning and offers the optimum control signal to uncertainties (Grondin et al., 2003). The lead-lag PSSs permit a support function stabilization signal to the diesel, hydro generator, PV solar cell, and DFIG of the given AC Microgrid to enhance the stability. Figure 8 represents the execution of the various kinds of power oscillation damping controllers into the AC Microgrid power system.

3.1. Conventional lead-lag power system stabilizers (PSS)

The arrangement of conventional lead-lag PSSs enhances the damping performance of the power oscillation in terms of the low frequency oscillations and improves the system's small signal stability. The IEEE standards conventional lead-lag PSS framework is illustrated in Figure 9, considering a dead band, phase lead/lag angle compensation block, tunable gain block, filter-based washout block, and signal range limiter. The conventional lead-lag power oscillation damping controller transfer function is depicted by Equation (12) while the feedback signal has been selected as the rotor speed of the generator (Zhang et al., 2012).

$$U_i = K_i \frac{sT_w}{1+sT_w}\left[\frac{\left(1+sT_{i1}\right)\left(1+sT_{i3}\right)}{\left(1+sT_{i2}\right)\left(1+sT_{i4}\right)}\right]\Delta\omega_i \tag{12}$$

Here, K_i is the gain of the conventional lead-lag damping controller; U_i is the output signal of the excitation system, T_ω washout time constant (0.5-10 sec.) T_{i1} & T_{i2} $\left(i=1,2,3\right)$ is denoted by the lead & lag time constant, and ω_i is represented by the speed deviation feedback signal.

3.2. IEEE standard multi-band power system stabilizers (MBPSS-4B)

IEEE PSS-4B standard multi-band PSS allows damping of the wide scale of low-frequency electromechanical oscillations. The MBPSS-4B comprises multiple operational bands, which have three tunable distinct frequency bands. The distinct bands are classified as low, intermediate, and high-frequency bands.

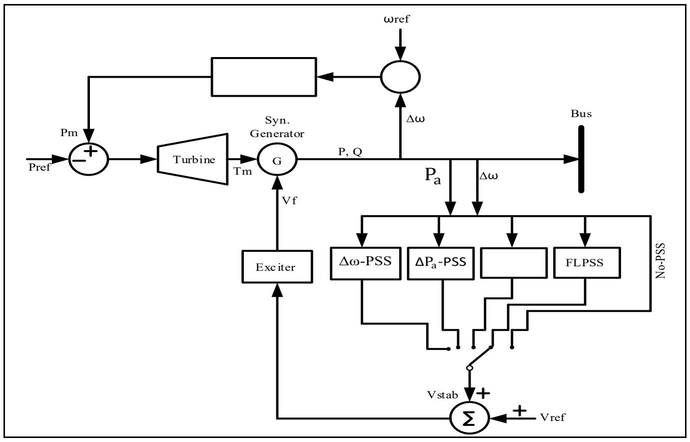

Figure 8. The essential organizations of a distributed generator with power oscillation damping controllers (Arora et al., 2023b).

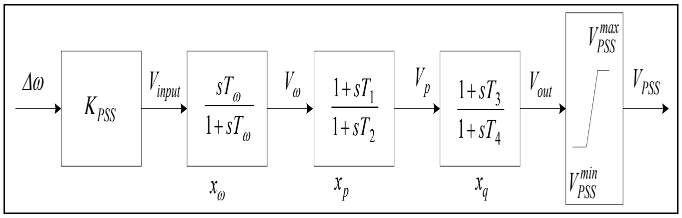

Figure 9. IEEE standard conventional lead-lag PSS based damping controller.

The low frequency is related to the global mode (under 0.2 Hz), the intermediate frequency band is related to the interred mode (0.2 to 0.8 Hz), and the high-frequency band is related to the local mode (0.8 to 4.0 Hz) (Kamwa et al., 2005). All three bands of MBPSS-4B consist of a bandpass filter, gain, and limiter blocks. The output responses of the three distinct bands are combined and proceed to the endmost limiter and provide the stable output in terms of the desired damping of the electromechanical oscillations. Figure 10 represents the conceptual block diagram of MBPSS-4B with input applied to the speed transducer and three responses of the frequency bands. Figure 11 represents the IEEE standard MBPSS-4B with three tunable frequency bands and limiters.

3.3. Fuzzy logic PSS (FL-PSS) damping controller

The arrangement of PSSs based on the fuzzy logic (FLPSS) controller depends on how humans seem to think and the degree of truth. Degrees of membership are represented in the fuzzy set elements required in fuzzy logic. Alternatively, each element is connected to multiple fuzzy sets. The value of the fuzzy set membership lies between 0 and 1. A crisp input variable is transformed into a fuzzy variable via the membership function. Figure 12. Basic working structure of fuzzy logic control (Dobrescu & Kamwa, 2004).

Figure 13 depicts the basic working scheme for fuzzy logic control, which consists of four primary functional units: the fuzzifier system block, the fuzzy inference expert system-based engine, the knowledge, rules, database, and the defuzzifier system. The membership function and the fuzzy rules that are used to generate the output from the fuzzy are correlated with the fuzzy inference process. Table 1 represents the interface mechanism of the 7x7 decision table of the FLPSS which presents the complete 49 if- then set of rules. This fuzzy controller's 49 (if-then rules) decision rules or 7x7 membership functions are designed with the aid of the provided input and output variables.

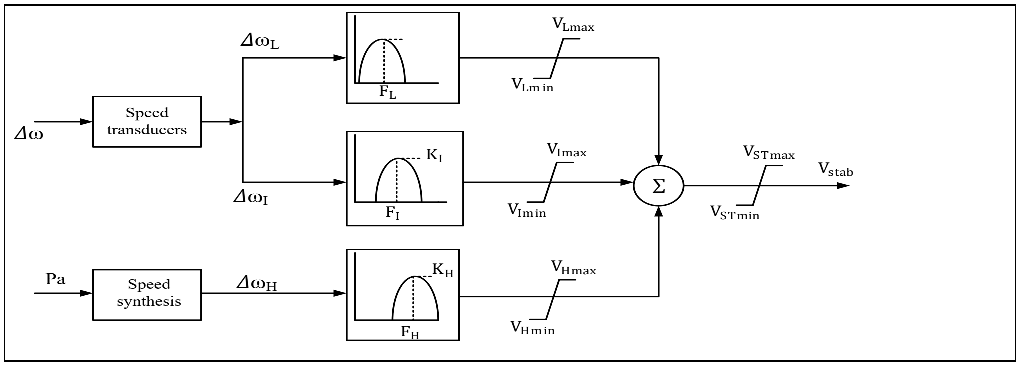

Figure 10. Conceptual block diagram IEEE standard multi-input type MB-PSS based damping controller

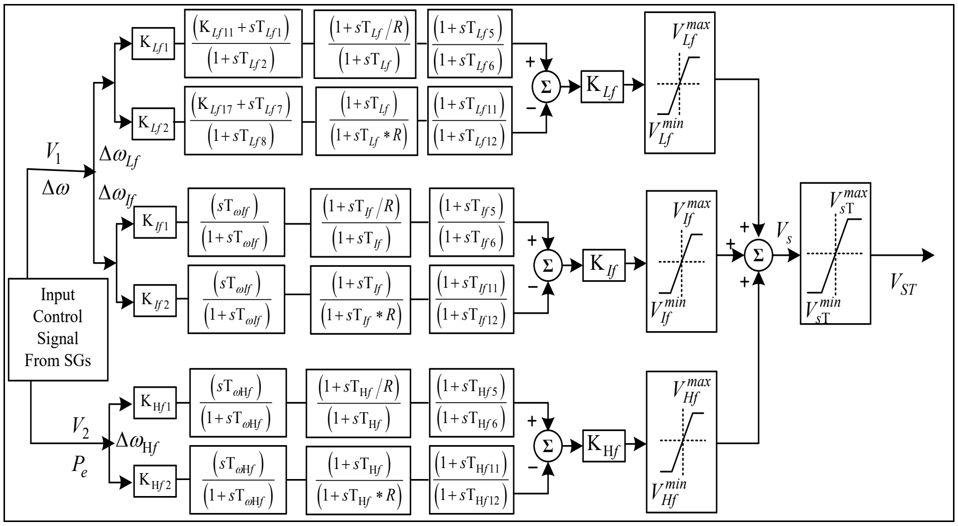

Figure 11. IEEE standard MBPSS power oscillation damping controller.

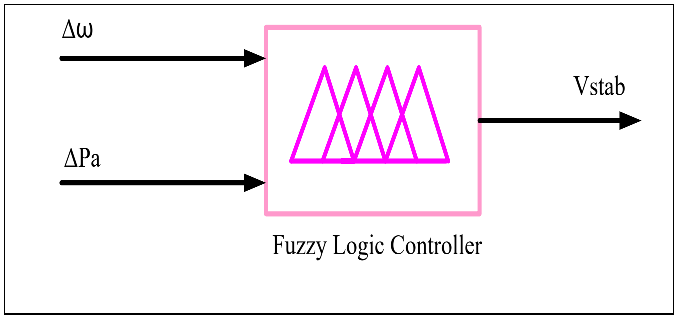

Figure 12. The basic working structure of fuzzy logic control.

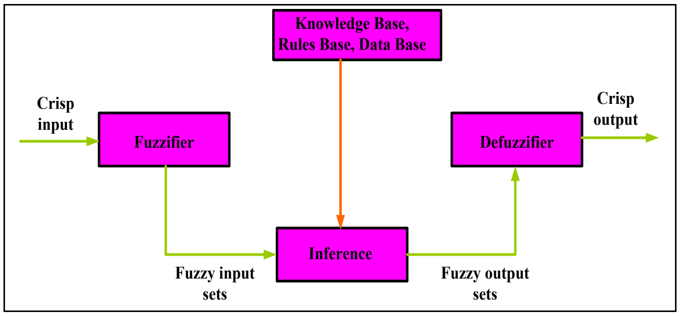

Figure 13. Block scheme of fuzzy logic control.

Table 1. Decision-making a table of 49 fuzzy rules.

Speed Deviation $(\Delta\omega)$	Acceleration Power (P_a)						
	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NM	NS	ZE	ZE	PM	PB	PB
PS	NM	NS	PS	PM	PM	PB	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	ZE	PM	PB	PB	PB	PB

The specified fuzzy rule-based table employs dual input signals, change in rotor speed (*Δ*ω) and acceleration active power (Pa), and only stabilizing output signal (Vstab). These input and output variables each use seven linguistic variables, ranging from negative big (NB) to positive big (PB) (Dobrescu & Kamwa, 2004) as indicated below in Table 2. Fuzzy input and output membership functions are depicted the Figure 14 to 16 respectively. Figure 17 represents the optimal control action surface view of the fuzzy logic PSS and gives the stabilized variable signal for improving the stability of the system.

4. Simulation results

This section examines the performance and robustness of the recommended controller in improving the dynamic stability of AC Microgrid power systems utilizing computer simulation. The outcomes illustrate the damping of the power oscillations with regards to LFOS of the AC Microgrid. The considered evaluation structure has 3-ϕ L-G fault at time=1 sec. with 9/60 sec. fault duration on the transmission line. The damping of the low-frequency oscillations of the system is improved by the implementation of various kinds of damping controllers like local/conventional lead-lag PSSs, IEEE standard MBPSS-4B, and fuzzy logic PSS (FLPSS) controllers. Conventional synchronous generators based hydro and diesel DGs damping performance represented with parameters such as rotor speed as well as angle deviation, and output active power are illustrated in Figures 18 to 20 and Figures 21 to 23. Figure 24 represents the deviation in rotor speed of the DFIG DG and Figure 25 represents the PCC bus voltage of the solar PV distributed generator respectively.

The effectiveness of a robustly developed FLPSS damping controller is optimum and offers superior damping assessments compared with conventional lead-lag PSS and MBPSS-4B damping controllers. Distinguishing the deployment of the multiple damping controllers, the recommended FLPSS controller exhibits greater robustness towards disturbances of LFOs and presents an improved damping response of the system compared to local or conventional lead-lag PSSs and MBPSS-4B.

This result presents a novel fuzzy logic-based power system stabilizer (PSS) that strengthens the power system's low frequency oscillation damping effectiveness and dynamic stability. Table 3 represents the damping performance of the different distributed generators with the deployment of the different power oscillation damping (POD) controllers. In this, the fuzzy logic power system stabilizer-based POD controller represents the best damping performance compared to the conventional PSS and MBPSS.

Table 2. I/P and O/P membership functions for fuzzy variables.

Membership Functions	
NB	Negative Big
NM	Negative Medium
NS	Negative Small
ZE	Zero
PS	Positive Small
PM	Positive Medium
PB	Positive Big

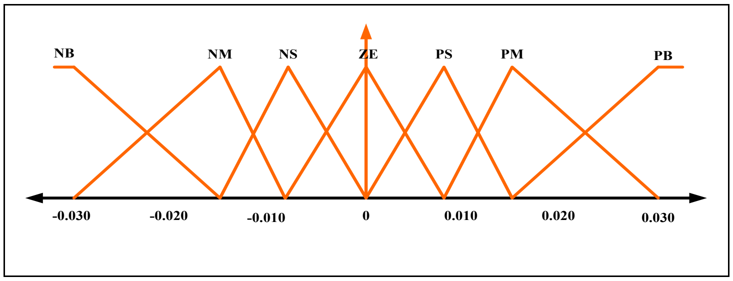

Figure 14. I/P membership function plot for rotor speed deviation (Δω).

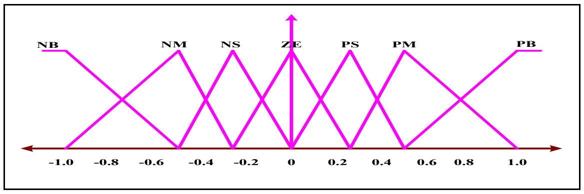

Figure 15. Representation of I/P functions with a membership using acceleration active power (P_a).

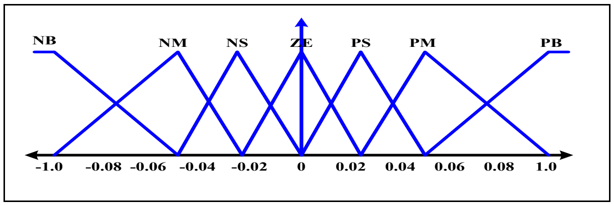

Figure 16. Representation of O/P functions with membership using stabilizing sign (Vstab).

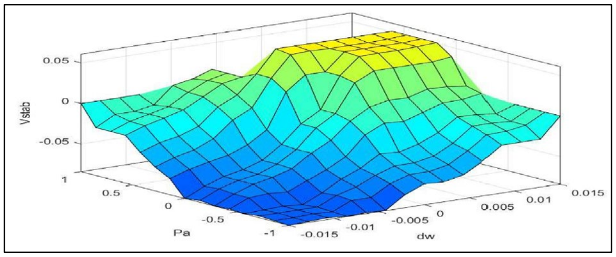

Figure 17. Decision surface viewer of FLPSS based power oscillation damping controller.

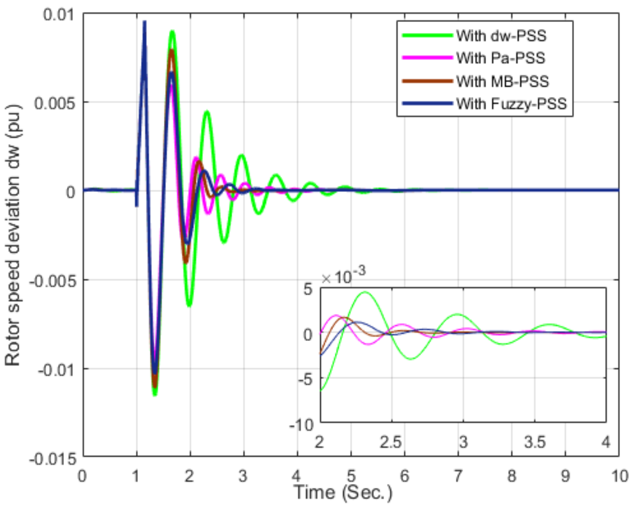

Figure 18. Power oscillation damping controllers' performance evaluation on rotor speed deviation ($\Delta\omega$) of the hydro generator (pu).

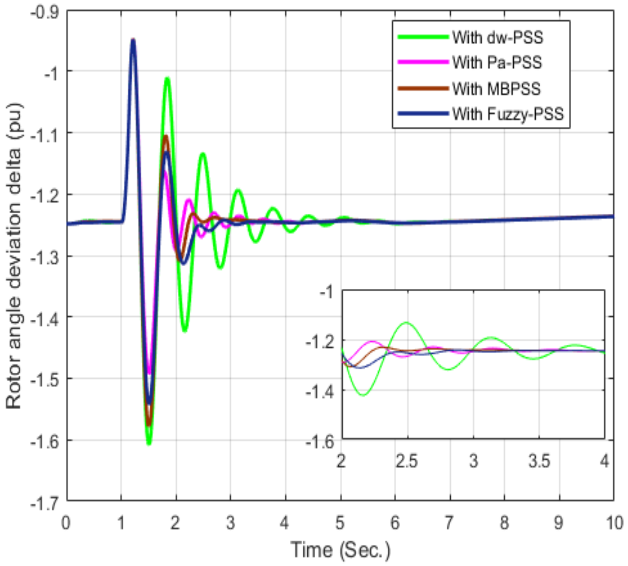

Figure 19. Power oscillation damping controllers' performance evaluation on rotor angle deviation ($\Delta\delta$) of the hydro generator (pu).

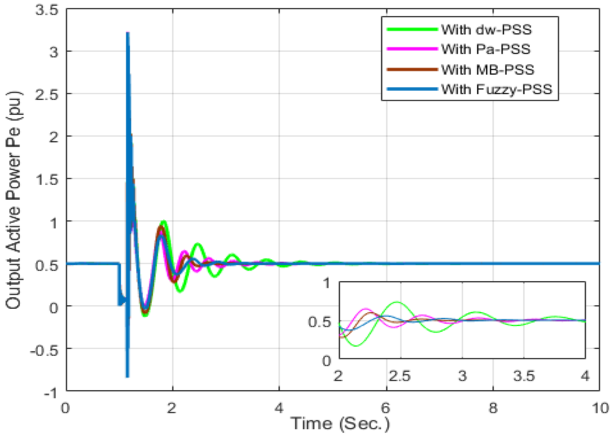

Figure 20. Power oscillation damping controllers' performance evaluation on active power output (Pe) of the hydro generator (pu).

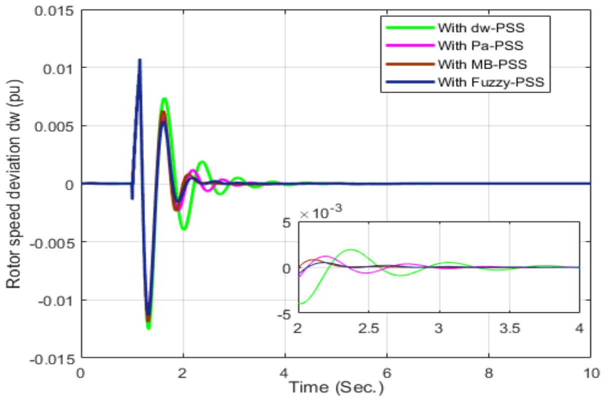

Figure 21. Power oscillation damping controllers' performance evaluation on rotor speed deviation ($\Delta\omega$) of the diesel generator (pu).

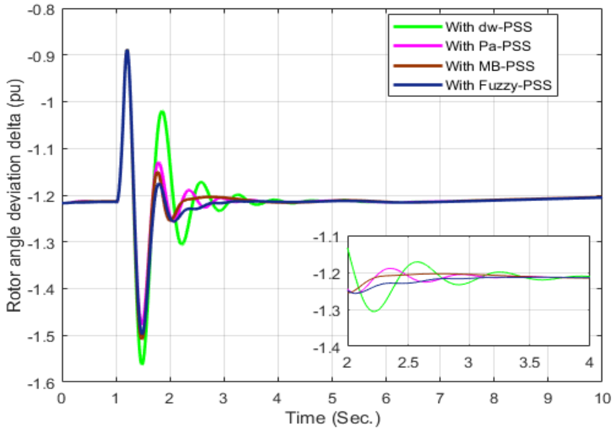

Figure 22. Power oscillation damping controllers' performance evaluation on rotor angle deviation ($\Delta\delta$) of the diesel generator (pu).

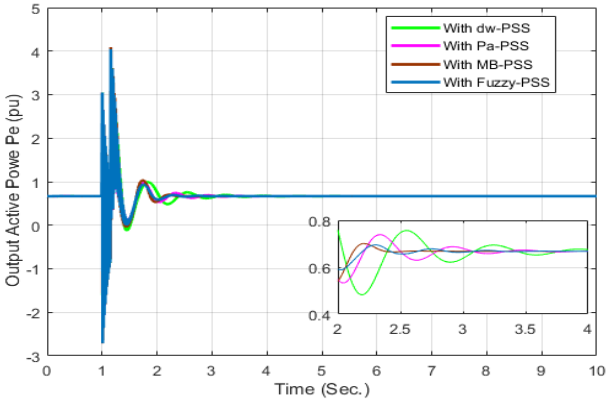

Figure 23. Power oscillation damping controllers' performance evaluation on active power output (Pe) of the diesel generator (pu).

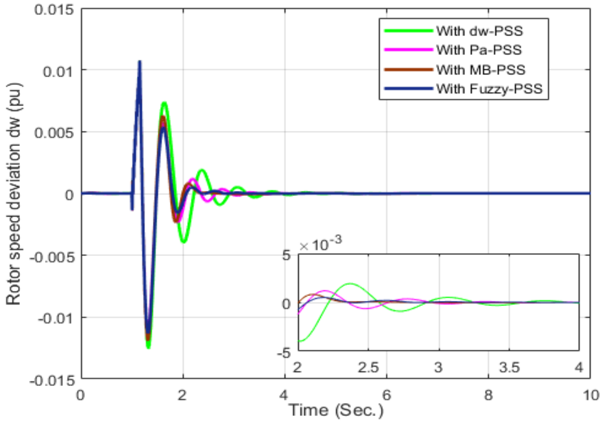

Figure 24. Power oscillation damping controllers' performance evaluation on rotor speed deviation ($\Delta\omega$) of the DFIG-WT (pu).

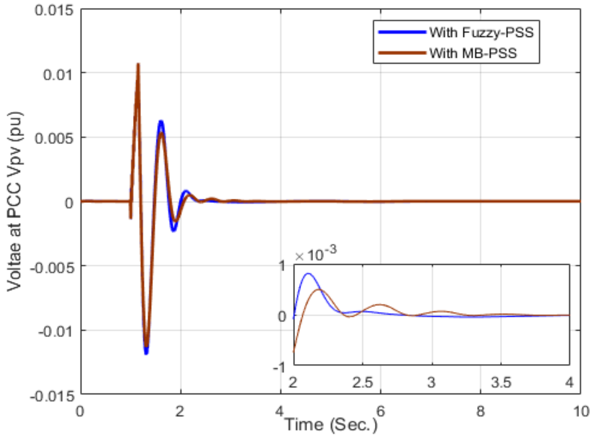

Figure 25. Power oscillation damping controllers' performance evaluation on Voltage at PCC PV (pu).

Table 3. Enhanced damping performance of the implemented controller in the AC Microgrid power system

Damping Controllers → Distributed Gen. ↓	NO-PSS	Δω-PSS	ΔPa-PSS	MB-PSS	FL-PSS
Diesel Gen.	0.02	0.05	0.06	0.08	0.09
Hydro Gen.	0.02	0.04	0.05	0.07	0.08
DFIG	0.02	0.05	0.06	0.07	0.09
Solar PV	0.0	0.01	0.01	0.06	0.08

5. Conclusions

This article investigates the dynamic damping performance of an AC Microgrid with the development of a robust fuzzy logic-based power oscillation damping controller. The execution of the different lead-lag power oscillation damping controllers enhances the system stability concerning low-frequency oscillations of the AC Microgrid. The effectiveness of various controllers such as conventional lead-lag PSS, MBPSS, and FLPSS is compared and analyzed with the disturbances in the AC Microgrid test system. Indeed, they show fuzzy logic PSS (FLPSS) satisfied the essential condition of the system as good robustness and good damping performance compared with the lead-lag PSS and MBPSS. It illustrates the capability and effectiveness of the fuzzy logic PSS (FLPSS) in the AC Microgrid system.

For further research, investigate the performance of the AC Microgrid in the imperfect communication medium such as noise and time delay in the control signal. This optimum control signal is influenced by an imperfect communication medium which affects the stability of the system. In this situation, investigates the effectiveness of the FLPSS in the system for dampening the low frequency oscillation.

Conflict of interest

The authors have no conflict of interest to declare.

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