Coordinated Designs of Fuzzy PSSs and Load Frequency Control for Damping Power System Oscillations Considering Wind Power Penetration

Nesrine Mekki and Lotfi Krichen

Abstract The damping enhancement of power system oscillations remains one of the challenging current interests for secure and reliable operation. This paper presents a comprehensive overview of a novel control scheme that considers synchrophasors and Power System Stabilizers in coordination with an optimized Load Frequency Control loop in order to resolve the undamped local and wide-area oscillatory troubles. Accordingly, a Robust Fuzzy PSS using local signals is first examined. Additionally, an Inter-Area PSS based on high-sampling rate phasor measurement unit is investigated. In fact, using time synchronized measurements as control input signals will participate effectively in monitoring the energy management process. Thus, another configuration mixing local and remote control inputs of a Mixed-PSS is proposed. Performances of these PSSs are evaluated in coordination with a tuned PI-based load frequency control design under different operating conditions. Results on a modified 9-Bus IEEE test system including DFIG wind turbines are reported in order to justify the proposal's applicability.

Keywords Phasor measurement unit · Load frequency control · Inter-area oscillations · Power system stabilizer · Fuzzy logic controller · Damping enhancement

Nomenclature

LFC	Load Frequency Control
IAPSS	Inter-Area Power System Stabilizer
RFPSS	Robust Fuzzy Power System Stabilizer
MPSS	Mixed-Power System Stabilizer

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DFIG WTs	Doubly Fed Induction Generator Wind Turbines
ACE	Area Control Error
TG	Turbine Governor
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
PSS	Power System Stabilizer
MB-PSS	Multi Band-Power System Stabilizer
FLC	Fuzzy Logic Controller
WACS	Wide Area Control Systems
PMU	Phasor Measurement Unit

1 Introduction

Recently, with the continuous increasing of electricity demand and high complexity of power grid interconnections, power systems will be eventually vulnerable to several problems during the system operation mainly caused not only by low frequency oscillations but also by inter-area oscillations. In fact, poorly-damped oscillations may lead considerably to system wide breakups especially under severe operating conditions. As local measurements based controls have restricted modal observability [1], using wide-area signals control determinations in such circumstance could be considerably beneficial in damping inter-area oscillations. Hence, in order to enhance the stability of power system swings prompted by these oscillatory modes, Power System Stabilizer (PSS) installation is economically and effectively adopted. Particularly, conventional PSS is not able enough to damp sufficiently inter-area oscillations. Getting in real time the system state variables would certainly be effective. Thus, the use of fast communication devices like PMUs will facilitate mostly the Wide Area Control Systems functionalities [2] and allow consumers to participate rationally in the electricity markets especially during peak demands when the system is more susceptible to experience the instability problem.

Traditionally, candidate input signals which are all locally available at the power plant ensure supplementary control action over the generator excitation system. Later, several advents use remote signals that are derived from PMUs as PSS inputs including local signals of the remaining plants [3]. Primarily, this technology affords globally-synchronized measurements of current and voltage phasors, phase angles, line flows and frequency resulting in generating accurate system-wide data sets mainly appropriate for damping targets. Over the past decades, several approaches have been suggested to damp local and inter-area oscillations. Some of them consider different control devices like PSS and FACTS [4] while others are suitable for operational conditions. Literately, various researchers have been presented a global PSS [5] based on multiple methods such as mixed integer non-linear programming, genetic algorithm-based dynamic search spaces and deviation-error vector and dynamic feedback control signal scaling [1, 5]. Likewise, another review has been specified several basis in PSS design including frequency response method, modal decomposition method [6], adaptive wide area PSS, and Eigen-structure-based performance index [7]. Other techniques like adaptive time delay compensator approach and fuzzy logic wide-area damping controller [8] have been stated for signal delays compensation purposes. In the same regard, damping inter-area oscillations stills as a challenging issue oriented primarily for system dynamic security enhancement as reported by Murali and Rajaram [9]. Currently, power system utility uses practically conventional PSS in their control process even it cannot provide satisfactory results over wider ranges of operating conditions [9, 10]. Equally, other types of PSS have been proposed such as proportional-integral PSS and proportional-integral derivative PSS. Subsequently, several studies regarding the PSS design have been preferred Fuzzy logic based technique. In fact, experienced human operators afford qualitative rules for effective control purposes especially in case of the unavailability of a mathematical model for the power plant [9]. Similarly, in order to improve the performance of Fuzzy logic based PSSs, Hybrid PSSs using fuzzy logic and/or neural networks or Genetic Algorithms have been illustrated in some literature surveys [10].

One of the most important aspects for damping unstable inter-area oscillations is to select the appropriate control signals. Over the last years, many procedures have been industrialized and verified to damp these oscillations by using both of local and global signals. Some of them focused on the signal type while the others taken into account the signal selection methods. Commonly, generator speed, active power and terminal-bus frequency are used widely as PSS input signals. For local control, generator speed deviations is mostly selected as an input signal [11]. Further studies in [12] have been chosen angle differences between buses as input signal. In fact, several methods based on modal observability have been developed for input signal selection in the literature. In [13], the interchanged active power of lines have been proposed as a stabilizer global signal for damping improvement aims. This input signal ensures high inter-area modes observability under different operating conditions. Using wide-area signals, the power transfer could be maximized. Another review that is based on sensitivity analysis of eigenvalues has been investigated in [8, 9, 14] to identify the transmission lines that are involved in each swing mode while analyzing the modal observability related to the network variables like voltage and current phasors which are delivered by PMUs. In [15], the clustering algorithm is recommended. Correspondingly, a comparison between geometric and residue approaches for selecting the global signal has been mentioned in [16]. As well, other methodologies based on virtual generators concept and trajectory-based supplementary damping control have been literately reported [15, 17]. Additionally, thorough attempts have been studied the PSS control signals using the center of inertia concept and calculating the frequency damping ratio for each inter-area mode [18].

In addition to PSSs control, modern energy management systems associate another multi-level supervisory schemes such as importantly the load–frequency control (LFC). Actually, it is considered as an additional secondary control which increases damping the system oscillations. The first step in the LFC mechanism is to add an Area Control Error (ACE) that acts on the Turbine Governor's (TG) load reference settings [19]. It is a function of the exchanged real power deviations that the LFC desires to make zero. For a multi area system, different generation control approaches have been proposed literately since the 1970s [19, 20]. In [21], an overview regarding the LFC issue have been stated, it describes its schemes, system models, control procedures, load characteristics, and the mutual interaction with the renewable resources. Similarly, various approaches in relation with Proportional–Integral–Derivative (PID), adaptive structure, intelligent, and networked control schemes have been revealed. Pandey et al. suggested an LFC's survey for distribution and conventional power systems [22]. Rerkpreedapong et al. proposed two decentralized control designs [23] using the linear matrix inequalities method and Proportional-Integral (PI) controller which is tuned by the genetic algorithm. Likewise, the fuzzy controller is considered in [24]. Particularly, PI controllers are commonly used in industrial applications which aim to reduce the steady-state error to zero [25].

Almost, previous studies have been proven that optimally-tuned PSSs with local signals are not able enough to damp inter-area swings. Thus, the main contribution of this paper is to investigate a novel control scheme that combines a Robust Fuzzy Power System Stabilizer (RFPSS) with an optimized PI-based LFC in order to increase damping of power system oscillations and improve the dynamic performances. The availability of PMUs signals affords new accurate measurement sets that are evaluated alongside traditional local signals. Hence, a new Inter-Area PSS (IAPSS) design is proposed taking into account both of local and wide-area signals in order to regulate the generator excitation system and then provide better system response. In addition, another configuration mixing local and remote control inputs of a Mixed-PSS (MPSS) is suggested. The rest of paper carries out the simulation studies of a modified IEEE 9-bus test system including DFIG wind turbines to judge the control scheme applicability under different operating conditions.

2 Description of the Power System Under Study

The undamped oscillations problem is analyzed by considering a 3-machine, 9-bus IEEE test system, whose single line diagram is represented in Fig. 1. The system frequency is 50 Hz. The generator 'Gen 1' is connected to the reference bus. The standard system state is reconfigured by replacing the generators 'Gen 2' and 'Gen 3' with new power plants which involve new control schemes. Each area is equipped with the performed PSSs and an optimized LFC process. Effectiveness of these controllers will be tested whenever incorporating DFIG wind turbines into the power system with different rates under different operating conditions in an advanced step.

- F_i: Frequency of a PMU-Equipped Generator, in Hz.

With I = 1, 2 (when Considering a Two-Area System Where Each Area Includes One Generator).

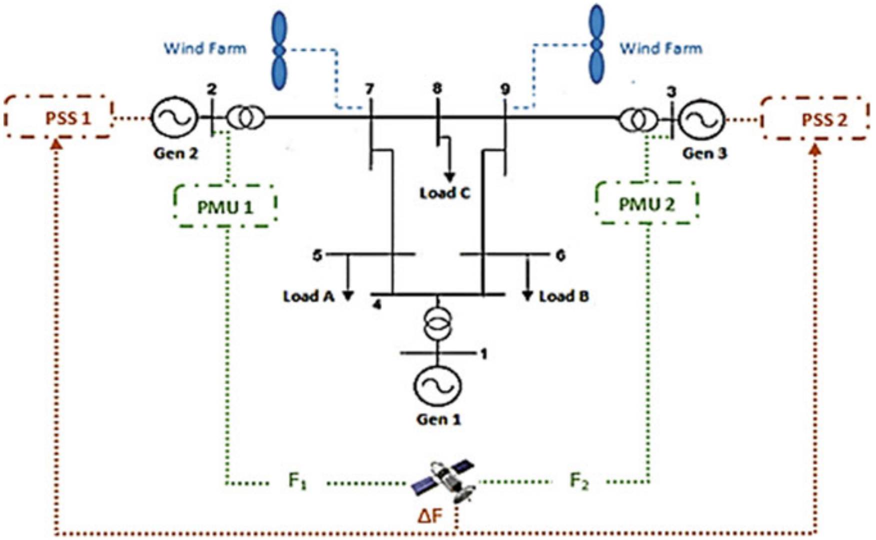


Fig. 1 Single line diagram of a 3-machine, 9-bus IEEE test system

3 Proposed Control Scheme

3.1 PSS-Based Local Control

Literately, compared to conventional PSSs, fuzzy logic based PSSs show better operational performances. In fact, by utilizing the output values of the power plant, it could apply the appropriate control actions in conformity with the rule-base. The key feature of a fuzzy controller is that it handles approximate data in a systematic way. It is ideal for modeling complex systems where an inexact model or ambiguous knowledge exist and for controlling non-linear systems [26]. Typically, the main configuration of a FLC consists of four basic components: selection and fuzzification of the input variables, fuzzy rule identification, rule inference and defuzzification. The dynamic performance of the system is primarily defined through its state variables which are taken as input signals to the proposed FLC. The fuzzified input and output variables are expressed into linguistic variables which are distinguished by different labels and membership functions. In fact, several studies have been reported that seven linguistic variables are practically enough, but, although the control accuracy will be improved as much as the number of variables increase, the computational time will rise too. In addition, choosing the appropriate membership function shape is crucial for a particular problem in relation with the fuzzy inference system. Comparisons between the different shapes such as triangular, trapezoidal, Gaussian and sigmoidal have been proved that both of the Gaussian and the triangular membership functions ensure similarly the most effective performance of the fuzzy logic based PSS design for all test conditions [27].

Table 1 Decision table for FLC

		Accelerating power						
		NB	NM	NS	Z	PS	PM	PB
Speed deviation	NB	NB	NB	NB	NB	NM	NS	Z
	NM	NB	NB	NM	NM	NS	Z	PS
	NS	NB	NM	NM	NS	Z	PS	PM
	Z	NM	NM	NS	Z	PS	PM	PM
	PS	NM	NS	Z	PS	PM	PM	PB
	PM	NS	Z	PS	PM	PM	PB	PB
	PB	Z	PS	PM	PB	PB	PB	PB

In the present work, the performed control scheme based on a RFPSS design uses the *rotor speed deviation ($\Delta\omega$)* and *the accelerating power (Pa)* as local input linguistic variables. The output linguistic variables elected for this controller is the *stabilizing voltage (V_s)*. Each variable is assigned seven linguistic fuzzy subsets. Each subset is associated with a triangular membership function, which is chosen for reasons of simplicity in terms of implementation and fast computation [28]. Particularly, the trapezoidal shape is designated only for the upper and the lower boundaries. The fuzzy sets that define the relation between the inputs and the output is done through a rule-base by utilizing seven linguistic terms which are Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Large (PL) such as given in Table 1. The rules are framed taking into account the nature of the system performance and the communal sense.

Generally, the *i*th rule can be presented as:

If *speed deviation ($\Delta\omega$)* is NB and *active power deviation* $(Pa)_i$ is NB then $(V_s)_i$ is NB.

Commonly, these control rules are consequent results from past experiences, intuitions, off-line simulations and expert operator decisions. The Mamdani inference mechanism and the Centroid method of defuzzification are selected for the proposed controller. Accordingly, the input–output control surface is obtained as displayed in Fig. 2.

Afterward, in order to justify the effectiveness of the proposed control scheme, the damping performance of the RFPSS is compared to a tuned Multiband-PSS (MB-PSS) that has already shown great improvements of the system response when compared to other types of PSSs. Its conceptual representation is depicted in Fig. 3. Actually, the tuning strategy of the MB-PSS is based on the symmetrical approach. Therefore, only six parameters are required. The center frequency and gain of each band of the lead-lag compensation block are suitably varied so as to get a nearly flat phase response at the frequency of interest. In fact, the differential filters are supposed to be symmetrical bandpass filters tuned at the center frequencies $\boldsymbol{F_L}$,$\boldsymbol{F_I}$ and $\boldsymbol{F_H}$.

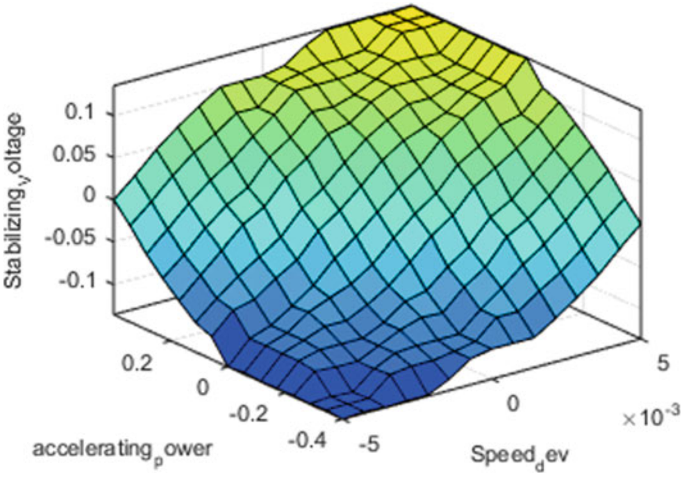
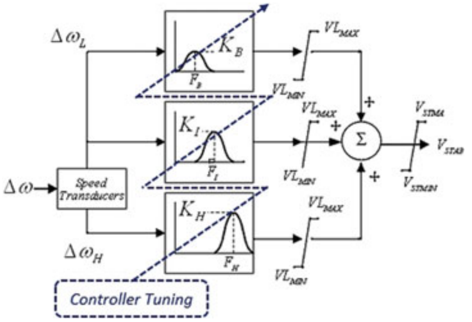


Fig. 2 Input–output control surface of RFPSS



▪ $\Delta\omega$	*Speed deviation (Hz)*
▪ F_B	*Center frequency of low frequency band*
▪ K_B	*Peak gain of the low frequency band*
▪ F_I	*Center frequency of the intermediate band*
▪ K_I	*Peak gain of the intermediate band*
▪ F_H	*Center frequency of the high band*
▪ K_H	*Peak gain of the high f band*
▪ V_{STMA}/V_{STMN}	*Limits imposed on the stabilizer's output*
▪ V_{STAB}	*Stabilization voltage (pu)*
▪ VL_{MAX} /VL_{MN}	*Limits imposed on the output of the bands*

Fig. 3 Conceptual representation of the tuned MB-PSS

The peak magnitude of the frequency responses is settled individually through the three gains $\boldsymbol{K_L}$, $\boldsymbol{K_I}$ and $\boldsymbol{K_H}$.

Based on the literature review [29], the MB-PSS parameters are optimally tuned and summarized in Table 2.

The PSS structure is based on three separate working bands. The first band presents the low band which is associated with global oscillation modes. The intermediate one is related to inter-area modes while the high band deals typically with the local modes. Each band is composed by a differential bandpass filter, a gain, and a limiter. In order to guarantee robust damping of the existing electromechanical oscillations, this PSS may include at all frequencies of interest reasonable phase advance that will compensate the inherent lag between the resultant electrical torque and the field excitation.

Table 2 Optimal MB-PSS settings

R	$\boldsymbol{V_{smax}}$	$\boldsymbol{V_{smin}}$	$\boldsymbol{V_{Imax}}$	$\boldsymbol{V_{Hmax}}$	$\boldsymbol{V_{Imin}}$	$\boldsymbol{V_{Hmin}}$	$\boldsymbol{V_{Lmin}}$	$\boldsymbol{V_{Lmax}}$	$\boldsymbol{K_L}$	$\boldsymbol{F_L}$	$\boldsymbol{K_I}$	$\boldsymbol{F_I}$	$\boldsymbol{K_H}$	$\boldsymbol{F_H}$
1.2	0.1	−0.1	0.6	0.6	−0.6	−0.6	−0.02	0.02	6	0.19	30	1.1	150	12

3.2 PMU-Based Wide-Area Control

Depending on the control design purposes, some signals are better competitive candidates than others. Lately, global signals measured directly by PMUs are considered favorably as new alternatives to local signals. The $\Delta\omega$ signals must be synchronized whenever used [30]. Till date, the aspect of PSSs using PMU control input signals has not been addressed in the literature but currently being investigated by numerous researchers. PMU is a high-accuracy platform that could contribute valuably to the dynamic monitoring of transient processes in modern electric power systems. Actually, it samples real-time values of currents and voltages. The time synchronization through GPS allows comparing the measured synchrophasors from different locations far apart and providing situational awareness which diminishes uncertainty in the decision-making.

The PMU block used in this paper is inspired by the IEEE Std C37.118.1-2011. It is based mainly on a Phase-Locked Loop which calculates the positive-sequence component of the input signal. In fact, the three-phase PLL tracks evidently the phase and frequency of the sinusoidal three-phase signal via an internal frequency oscillator which is regulated through the control system in order to keep the phase difference at zero. Afterwards, the positive-sequence components including the magnitude and phase of the input signal are computed over a running window of one cycle of the fundamental frequency that is tracked previously throughout the PLL closed-loop control system. Importantly, the reference frame needed for the computation is set via the angle given also by the PLL and varying between 0 and 2*pi, synchronized on zero crossings of the positive-sequence of the fundamental. The PMU outputs define the magnitude, the phase, the frequency and the rate of change of frequency of the positive-sequence component of the input signal at the fundamental frequency. The sample time T_S is expressed as follows:

$$T_S = \frac{1}{f_n \times N_{sr}} \tag{1}$$

f_n Nominal frequency, in Hz.

N_{sr} Sampling rate, in point/cycle.

3.2.1 PSS with Two Remote Inputs

In the present study, a new inter-area fuzzy based PSS design (IAPSS) is suggested considering two input signals which are the *frequency difference (Δf)* and its *differentiation ($\Delta\dot{f}$),* and a single output which represents *the stabilizing signal (V_s).* Beforehand, each generator terminal is equipped with one PMU to measure accurately the desired input signals which will vary as well as the consumed power changes. The exciter input of each generator is controlled using the generators frequencies given

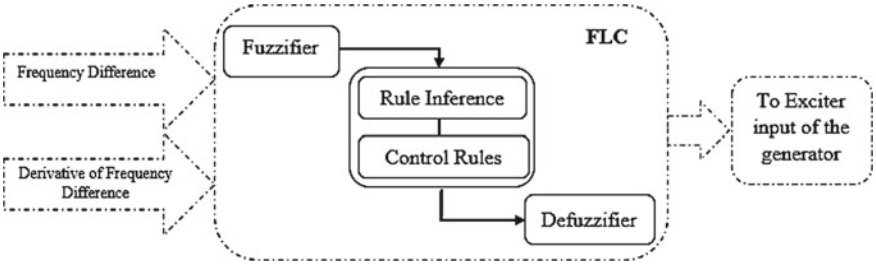


Fig. 4 Block diagram of FLC for one area

by the existing PMUs. These PMUs outputs are evidently considered as wide area measurements that communicate each generator to the remaining areas constituting the power system. Based on this scheme, inter-area controllers are performed referring to the fuzzy inference mechanism mentioned in the previous section. The basic configuration of a Mamdani FLC is presented in Fig. 4.

3.2.2 PSS with Remote and Local Inputs

As global signal's involvement shows satisfactorily results regarding the damping of system oscillations, further examinations combining one local PSS input and one remote input obtained by PMU are carried out. In fact, in the present work, another fuzzy based PSS design is performed considering a mixture between *the frequency difference* (Δf) as a global input signal and the *accelerating power (Pa)* as a local input signal.

The main objective is to investigate superior local mode damping with higher inter-area mode observability by using simultaneously local and global control input signals. Accordingly, performances of the suggested Mixed-PSS (MPSS) configuration are compared later against the previously-mentioned designs of PSSs Viz. RFPSS and IAPSS controllers.

4 Involvement of LFC Design

The aim of this section is to discuss the efficiency of combining an enhanced LFC design with the performed PSSs in order to increase the damping of system oscillations. In fact, the LFC scheme will involve an appropriate control loop that is able enough to adjust the system frequency to the scheduled set point values effectively after any load change or fault occurrence. Particularly, PI controller is chosen to be applied for the current LFC system due to its simplicity in execution and its ability to afford fast response and zero steady state error. Actually, choosing randomly the controller parameters will not guarantee the best dynamic performances regarding the system stability. Hence, special attentions are given for establishing an optimal tuning approach of the PI parameters in order meet the desired requirements whenever exposed to load demand variations or sudden disturbances.

The Nonsmooth H_∞ minimization technique is adopted in the present paper for optimal tuning purposes. This approach is adopted in multiple control designs for damping of large power systems [31]. It solves in general the following constrained problem:

$$Minimize \max_i f_i(x) \tag{2}$$

$$Subject\,to \max_j g_j(x) < 1, \;\; for\; x_{\min} < x < x_{\max} \tag{3}$$

The optimization is reached by resolving a sequence of unconstrained subproblems given by:

$$\min_x max(\alpha f(x), g(x)) \tag{4}$$

$f_i(x)$*and* $g_j(x)$*: Normalized values of soft and hard tuning requirements.*

x: vector of PI parameters to tune.

x_{min} *and* x_{max}*: Minimum and maximum values of the free parameters of the controller.*

α: *A multiplier which is adjusted until convergence to the solution of the original constrained problem.*

The auxiliary action of the LFC based-tuned PI controller is incorporated into the studied power plants in coordination with the performed designs of PSSs Viz. RFPSS, IAPSS and MPSS as depicted in Figs. 5, 6 and 7, respectively, in order to restrain the system deviations efficiently while maintaining fast response and robust stability. In an advanced step, the simulation results will address mainly the effectiveness of

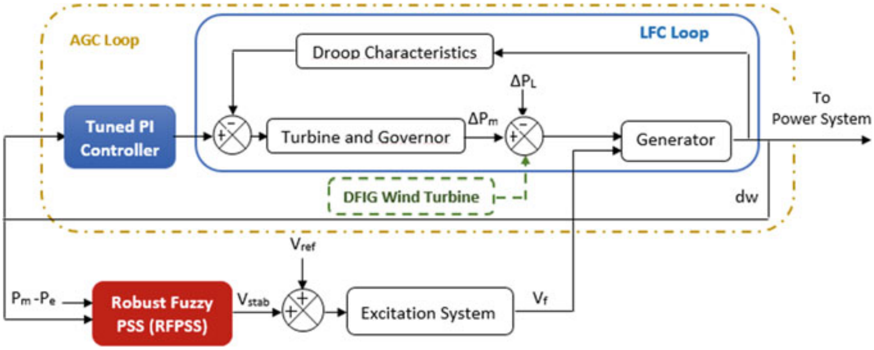


Fig. 5 Block diagram of the LFC-RFPSS control scheme in a single area power plant

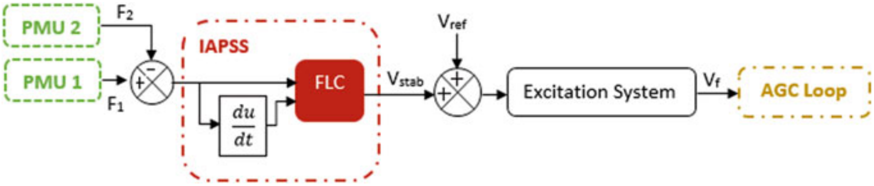


Fig. 6 Block diagram of the LFC-IAPSS control scheme in a single area power plant

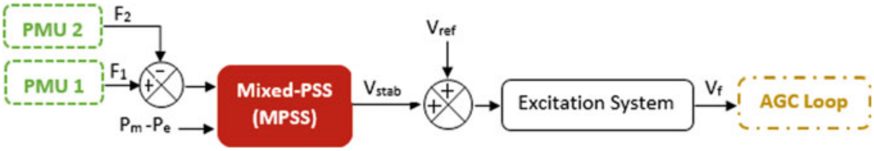


Fig. 7 Block diagram of the LFC-MPSS control scheme in a single area power plant

the suggested control scheme whenever integrating the wind energy sources in the power system.

5 Simulation and Discussion

For reasons of simplicity, this study elects as example of concern the generator number 2, 'Gen 2', and a variable load located at the nearest bus, 'Bus 8'. The system under study is subjected to an increase in load demand at 3 s and a three-phase fault

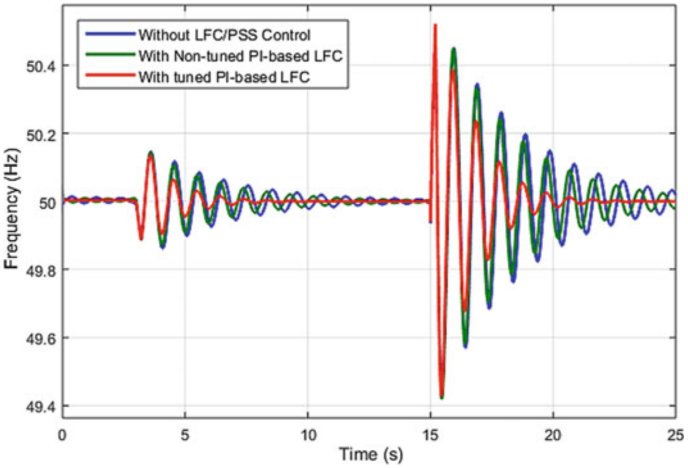


Fig. 8 Frequency response measured at generator 'Gen 2'

of 0.2 s duration on that bus at 15 s. The main interest first is to evaluate the efficiency of applying an optimized LFC loop in reaction to the changing loading conditions. Hence, Fig. 8 which presents different frequency responses of 'Gen 2', from which, it can be noted that the tuned PI-Based LFC shows better damping for the frequency oscillations than the non-tuned controller. Actually, during overloading and fault conditions, the frequency fluctuations persist for a long period, but, the application of the tuning process helps the governor system to absorb effectively the arising swings which are attenuated gradually in number and amplitude and maintain finally a frequency recovered close to the scheduled values.

5.1 Local Versus Wide-Area Damping Control

Generally, local PSSs are not able enough to provide global and real-time vision of power systems. Hence, the inclusion of accurate remote inputs in the PSS's control loop becomes a key factor in considering better dynamic performances for wide-area oscillations. The major goal of the present work is to investigate the efficiency of the designed controllers in combination with the suggested LFC loop whenever exposed to sudden disturbances. For instance, several comparisons between the performed PSSs among different operating conditions are made to achieve further damping enhancement. The simulation results obtained for the frequency response of the machine of concern are shown in Fig. 9.

It is noticeable that the system operating without any control scheme is highly oscillatory according to Fig. 8. Yet, the MPSS with LFC integration shows the most effective output response for reducing the overshoot and settling time. Actually, all

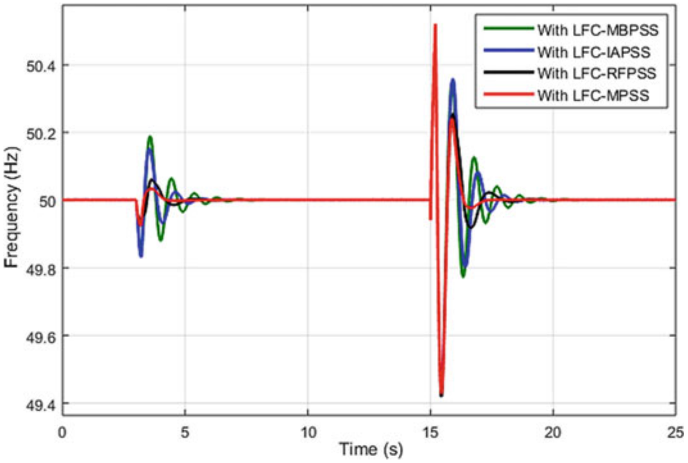


Fig. 9 Frequency response measured at generator 'Gen 2'

the oscillations decay much faster by utilizing the mixed configuration of local and remote inputs than using the tuned MBPSS or RFPSS or IAPSS designs.

The numerical values of the frequency response for different cases are mentioned in Table 3. Under normal operating conditions, when the machine is equipped with the proposed MPSS scheme in coordination with the LFC design, the peak overshoot and settling time are reduced reaching the value of 0.04 Hz and time of 1 s. Compared to the other responses, this combination shows more stable performances too when the system is forced by a disturbance.

As well, compared to the remaining types of PSSs, the designed MPSS demonstrates powerful capabilities in regaining the nominal values and keeping the system equilibrium as shown in Figs. 10 and 11 which display the electromagnetic torque and the rotor angle deviation of the generator of concern 'Gen 2', respectively.

These results confirm the critical role that the MPSS plays in damping the maximum of undesirable fluctuations at a short period of time in reaction to load

Table 3 Frequency responses for different scenarios

	Normal operating conditions		Fault operating condition	
	Peak overshoot (Hz)	Settling time (s)	Peak overshoot (Hz)	Settling time (s)
With LFC-MBPSS	0.18	3.8	0.34	4.7
With LFC-IAPSS	0.14	2.35	0.32	3.23
With LFC-RFPSS	0.08	1.76	0.24	2.9
With LFC-MPSS	0.04	1.17	0.22	2.05

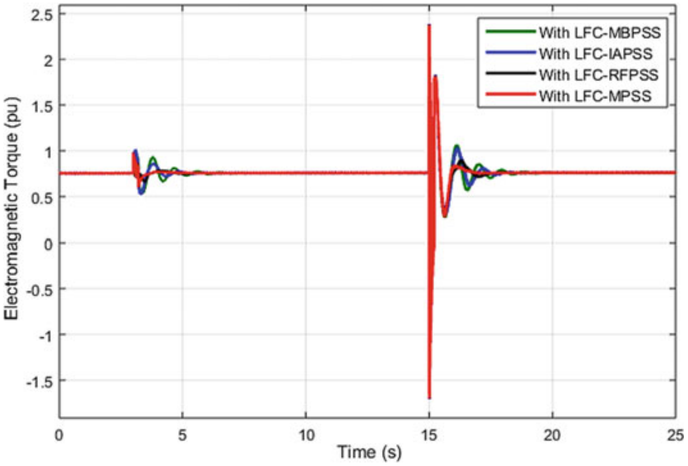


Fig. 10 Electromagnetic torque measured at generator 'Gen 2'

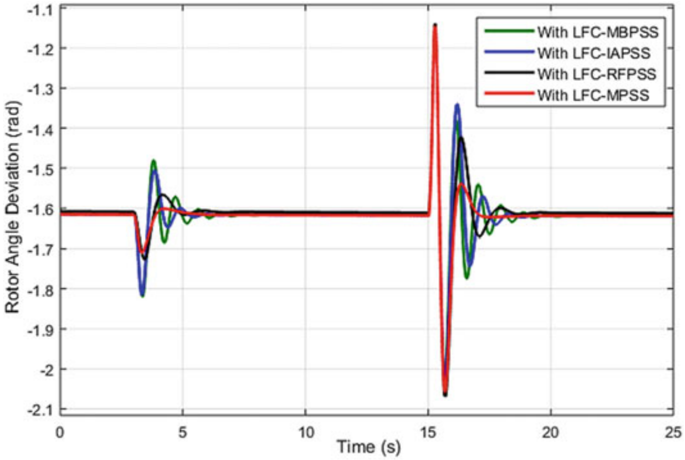


Fig. 11 Rotor angle deviation measured at generator 'Gen 2'

Table 4 Electromagnetic torque responses for different scenarios

	Normal operating conditions		Fault operating condition	
	Peak overshoot (pu)	Settling time (s)	Peak overshoot (pu)	Settling time (s)
With LFC-MBPSS	0.25	2.9	0.4	3.8
With LFC-IAPSS	0.2	1.47	0.33	2.9
With LFC-RFPSS	0.18	0.58	0.16	2.35
With LFC-MPSS	0.16	0.29	0.08	1.7

demand variations and under fault condition. Correspondingly, the different electromagnetic torque responses are improved significantly as summarized in Table 4.

Referring to these numerical results, the performed control design of the combined LFC-MPSS produces effectively not only the least peak overshoot values but also the least settling time of all responses. Therefore, an important increase in damping system oscillations is obviously checked under different operating conditions. Furthermore, the stability enhancement is achieved by accelerating the settling time and reducing the peak overshoot of rotor angle deviation as shown in Table 5.

Compared to the responses of the remaining cases, it is proven that coordinated LFC-MPSS control scheme is able enough to provide the best performance while maintaining reduced values of the peak overshoot and settling time under normal and fault operating conditions.

Table 5 Rotor angle deviation responses for different scenarios

	Normal operating conditions		Fault operating condition	
	Peak overshoot (rad)	Settling time (s)	Peak overshoot (rad)	Settling time (s)
With LFC-MBPSS	0.12	3.75	0.27	4.75
With LFC-IAPSS	0.1	2.75	0.22	4
With LFC-RFPSS	0.04	2.5	0.2	3.5
With LFC-MPSS	0.01	2	0.07	2.5

5.2 Wind Power Integration

In order to test the efficiency of the proposed control scheme in improving the system stability in presence of DFIG wind turbines, diverse penetration levels ranging from 10 to 30% are examined. For that, two wind farms are connected to bus 9 and bus 7, near to the performed power plants (‘Gen 3’ and ‘Gen 2’), respectively. Each wind farm is consisted of DFIG wind turbines which are connected to a local 25 kV distribution system and rated 9 MW each. Initially, the simulation results are carried out considering only the LFC loop. The dynamical frequency responses of the generator of concern, ‘Gen 2’, for three levels of wind power penetration are presented in Fig. 12 under normal and fault conditions.

Clearly, injecting an intermittent wind energy with rates of 10 and 20% reveal relatively similar results. However, compared to these cases, when wind penetration increases up to 30%, the frequency stability is significantly degraded. Hence, the rest of analysis will be conducted chiefly for a penetration level of 20% of wind power

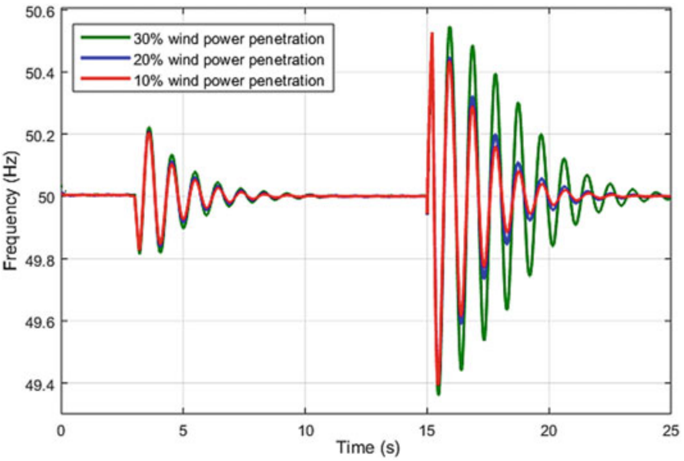


Fig. 12 Frequency response of generator ‘Gen 2’ with three levels of wind penetration

to keep stable operation of generators. The installed DFIG wind turbines export to the test system a total power of 72 MW.

Almost, wind energy incorporation affects the power system functionality. As much as the electrical power is produced, small fluctuations will definitely occur. Additionally, fault operation condition may force the system to lose its dynamic stability. Accordingly, DFIG wind turbines will operate till the fault is cleared. During the disturbance, the wind farms generate sufficient reactive power that supports the system outputs. The performed controllers try then to increase damping the appearing swings and approximatively adjust the waveforms to the specific set points as proven in Fig. 13 which depicts the frequency responses of the machine under test using different PSSs in coordination of the LFC loop.

The frequency response yields the best damping performance using the proposed LFC-MPSS control design when compared to the remaining operation scenarios. Accordingly, the mixed PSS configuration demonstrates satisfactorily results revealing rapidly-damped out oscillations.

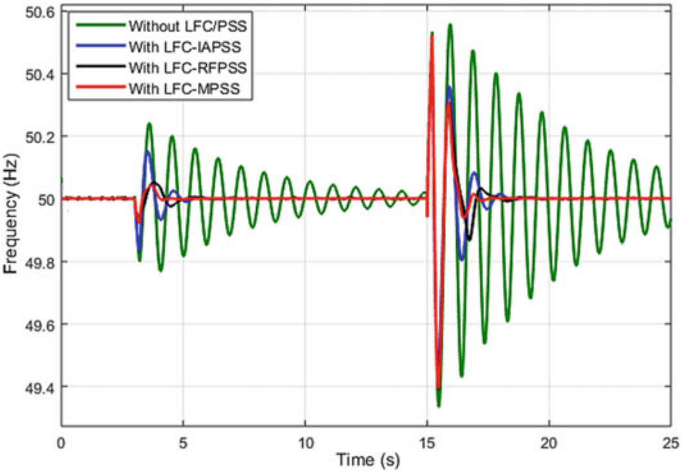


Fig. 13 Frequency response measured at generator 'Gen 2'

Table 6 Frequency responses for different scenarios considering DFIG WTs integration

	Normal operating conditions		Fault operating condition	
	Peak overshoot (Hz)	Settling time (s)	Peak overshoot (Hz)	Settling time (s)
Without LFC/PSS	0.23	>10	0.54	>10
With LFC-IAPSS	0.14	3.06	0.34	4.08
With LFC-RFPSS	0.05	2.55	0.29	3.5
With LFC-MPSS	0.03	1.27	0.27	2.55

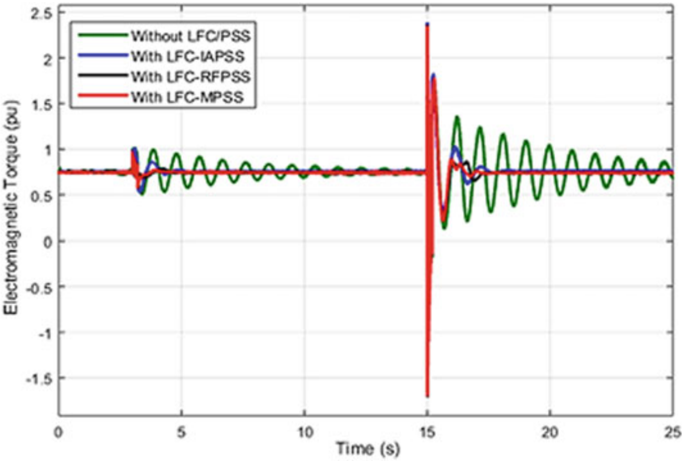


Fig. 14 Electromagnetic torque measured at generator 'Gen 2'

The numerical results are listed in Table 6 which proves that the frequency response improvement is achieved when the MPSS is integrated in the test system. Under normal operating conditions, the peak overshoot and the settling time are reduced significantly and reach the values of 0.03 Hz and 1.27 s, respectively. Likewise, comparison between the different simulated cases shows that combined LFC-MPSS design is able enough to damp effectively the frequency oscillations. The settling time and the peak overshoot are the least ones reaching the values 2.55 s and 0.27 Hz, respectively, when the system is subjected to a disturbance. Meanwhile, the dynamic stability margin of the system is kept within the permitted limits in presence of the intermittent energy of DFIGs WTs.

Further investigations on different operation scenarios prove the effectiveness of the proposal as depicted in Figs. 14 and 15 which show the electromagnetic torque and the rotor angle deviation of the generator of concern 'Gen 2', respectively.

It's noticeable that coordinating the designed LFC with the MPSS increased definitely the damping of system oscillations which take less time to stabilize and settle back to steady state. Along with an increase in load demand, the oscillatory swings are reasonably kept limited relatively at the scheduled values under fault conditions.

From Table 7, it is inferred that the settling times and amplitudes of electromagnetic torque oscillations are very high without adding any PSS. Yet, after the introduction of coordinated LFC-MPSS design in the system, the peak overshoot and settling times of oscillations are reduced at the values of 0.06 pu and 1.1 s, respectively, under normal operating conditions. Likewise, under fault condition, the simulation results show that the peak overshoot and the settling time are improved at the values of 0.12 pu and 1.76 s, respectively, compared to the remaining scenarios.

Equally, Table 8 proves that the coordination between the performed LFC and MPSS control designs is able to enhance the damping of the oscillatory response of rotor angle deviation. The peak overshoot is reduced and reaches the value of

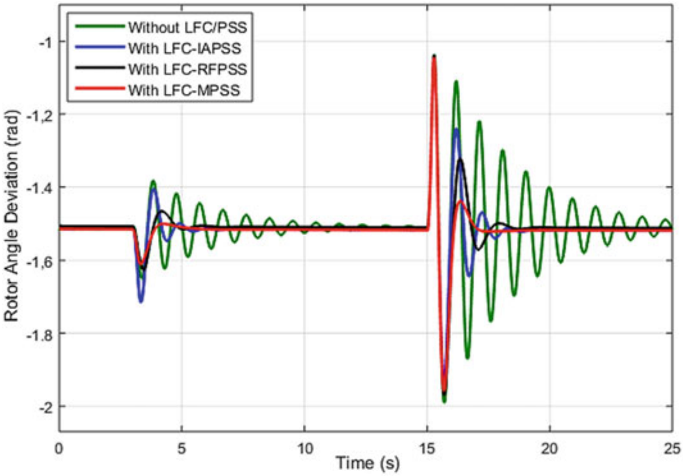


Fig. 15 Rotor angle deviation measured at generator 'Gen 2'

Table 7 Electromagnetic torque responses for different scenarios considering DFIG WTs integration

	Normal operating conditions		Fault operating condition	
	Peak overshoot (pu)	Settling time (s)	Peak overshoot (pu)	Settling time (s)
Without LFC/PSS	0.5	>10	1	>10
With LFC-IAPSS	0.25	1.76	0.5	3.23
With LFC-RFPSS	0.1	1.47	0.25	2.35
With LFC-MPSS	0.06	1.1	0.12	1.76

Table 8 Rotor angle deviation responses for different scenarios considering DFIG WTs integration

	Normal operating conditions		Fault operating condition	
	Peak overshoot (rad)	Settling time (s)	Peak overshoot (rad)	Settling time (s)
Without LFC/PSS	0.14	>10	0.4	>10
With LFC-IAPSS	0.12	2.77	0.28	3.6
With LFC-RFPSS	0.1	1.9	0.2	3.3
With LFC-MPSS	0.08	1.38	0.1	1.66

0.08 rad while the settling time is achieved at time of 1.38 s under normal operating conditions. These oscillations are more efficiently damped out reaching low overshoot and settling time with values of 0.1 rad and 1.66 s, respectively, when the system is subjected to a disturbance.

Accordingly, numerical and graphical results confirm the satisfactory performance of the proposed controllers in damping power system oscillations. In fact, compared to RFPSS and IAPSS performances, by using remote and local input signals, the MPSS shows improved and fast responses recovering the scheduled values in coordination with the optimized LFC loop under different operating conditions.

6 Conclusion

The present paper presents a novel control scheme that combines an optimized PI-based LFC with new designs of PSSs aiming mainly to increase the damping of power system oscillations. Great attention is given first to the LFC design which shows better responses whenever the loading conditions are unpredictably fluctuating. It is based on a tuned PI controller whose parameters are optimally set by using the H_∞ methodology. Additionally, a novel RFPSS regulator based on fuzzy system is investigated in coordination with the LFC design for system's damping improvement purposes. Furthermore, a review of wide-area damping control is discussed in this work. In fact, global measurements from PMUs are considered first as the input signals of the suggested IAPSS design. Later, a mixed configuration that combines single remote input with a local input is presented. The simulation studies on a modified IEEE 9-bus test system prove that the MPSS design yields the best and fast damping characteristics under different operation scenarios taking into account the impact of wind energy incorporation. In conclusion, the current work demonstrates that the application of real-time fuzzy logic PSS based PMU considering local inputs, whenever combined with an optimized LFC loop, exhibits high quality of the control signal that contributes in providing efficient dynamic system performances.

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