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Fuzzy Logic Stabilizers in a Wind Energy Distributed Generation System

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Abstract: This study proposes a new power system stabilizer based on fuzzy systems. The new controller is applied to a wind turbine generating system comprising of a wind turbine driving a 3-phase synchronous generator connected to a large power system. The new controller significantly improves system performance. The enhancement in the dynamic response of the system is verified through simulation results of a system under different operating points and exposed to both small and large disturbances. Extension to the wind energy distributed generation based multi-machine case is also included to illustrate the effectiveness of the proposed stabilizer in damping power system swing mode oscillations that follow disturbances.

Key words: Fuzzy system, power system, stabilizer, swing mode oscillation, dynamic

INTRODUCTION

Over the past 2 decades, interest in the use of environmentally friendly renewable energy resources has intensified. Of various alternative energy sources, wind energy is said to be one of the most prominent sources of electrical energy in years to come. The increasing concerns to environmental issues demand the search for more sustainable electrical sources. Wind turbines along with solar energy and fuel cells are possible solutions for the environmental friendly energy production. In this study, the focus is on the wind power as it is said to hit large integration in the near future. The challenge is to achieve system functionality without extensive custom engineering yet still have high system reliability and generation placement flexibility. Now-a-days, it is a general trend to increase the electricity production using Wind Energy Distributed Generation (WEDG) systems. If these systems are not properly controlled their connection to the utility network can generate problems on the grid side. Therefore, considerations about some technical barriers such as power generation safe running and grid synchronization must be done before connecting these systems to the utility network. WEDG systems have to overcome these technical barriers if it should produce a substantial part of the electricity (IEC, 2001).

In the wind energy based power system, the objective of the control strategy is to generate and deliver power as economically and reliable as possible while maintaining the voltage and frequency within permissible limits. The WEDG systems are conventionally equipped with Automatic Voltage Regulators (AVRs) to improve the system performance. Unfortunately, AVRs adversely affect stability (Demello and Corcordia, 1969). Exposed to disturbances such as wind variations operating point variations and short circuits power systems may exhibit unacceptable swing mode oscillations or loose synchronism. To damp and suppress these oscillations Power System Stabilizers (PSS) are normally incorporated (Yu, 1983).

Design and application of Conventional PSS (CPSS) has been the subject of continuing development for many years. The usual design approach for CPSS is based on linearized system model with fixed system parameters. Conventional power system stabilizers are based on linearized machine model and thus tuned at a certain operating point. However, WEDG systems are highly non linear systems. CPSS tuned at a certain operating point may not work properly for the actual plants. If the system drifts from the original operating point, the performance of a CPSS degrades significantly.

Alternative control techniques including self-tuning regulators, pole placement, robust control and pole shifting have been investigated for the design of power system stabilizers (Sadat, 2002; Soliman *et al.*, 2000). This involves obtaining a frequency response of the systems. There is a problem associated with it when noise is present.

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In recent years, fuzzy-logic control has been proposed for power system stabilization problems (El-Metwally and Malik, 1996; Malik and El-Metwally, 1998). Fuzzy logic controllers are nonlinear controllers based on the use of expert knowledge. This knowledge is usually obtained by performing extensive mathematical modeling analysis and development of control algorithms for power systems. Since, power system stabilizers are an analog or digital implementation of lead lag networks it turns out that a generic rule base is available in the literature to help in constructing such a controller (Malik and El-Metwally, 1998). Still, the design of a Fuzzy Logic Power System Stabilizer (FLPSS) requires the selection of the shape and parameters of the membership functions the size of the rule base and the rule inference mechanism.

This research proposes a new Fuzzy-Logic Power System stabilizer (FLPSS) that overcomes the Conventional Power System Stabilizer (CPSS) drawbacks. The proposed stabilizer is initialized using the small rule base of a FLPSS to ensure an acceptable performance. The rule base is then increased so that the stabilizer can cope with different operating conditions. The proposed stabilizer results in a satisfactory performance as compared to the CPSS.

MATERIALS AND METHODS

Fuzzy Logic Power System Stabilizer (FLPSS): The basic configuration of a pure fuzzy-logic controller is composed of four parts: The fuzzification; the knowledge base; the inference engine and the defuzzification (Fig. 1). The fuzzification is the process of mapping the input crisp values into fuzzy variables using normalized membership functions and input gains. The fuzzy-logic inference engine deduces the proper control action based on the available rule base. The fuzzy control action is transferred to the proper crisp value through the defuzzification process using normalized membership functions and output gains (Sivanandam *et al.*, 2007). The speed deviation, Δω and the deviation in accelerating power (Electrical power-mechanical power), ΔP of the synchronous machine are chosen as the inputs. The use of accelerating power as an input to the power system stabilizer has recently received considerable attention due to its inherent low level of torsional interactions (Malik and El-Metwally, 1998). Practical difficulties of eliminating the effect of mechanical changes appear to have been overcome by utilizing a heavily filtered speed signal which approximately corrects for mechanical power variations (Malik and El-Metwally, 1998).

The output control signal from the FLPSS1, U_{PSS} is injected to the summing point of the AVR (Appendix 1). Let the letters N, Z and P stand for the linguistic values negative zero and positive, respectively. Each of the FLPSS1 input and output fuzzy variables is assigned three linguistic values varying from Negative (N) to Positive (P). Each linguistic value is associated with a membership function to form a set of three normalized and symmetrical membership functions for each fuzzy variable as shown in Fig. 2. The values X_{max} and X_{min} represent maximum and the minimum variation of the input and output signals. These values are selected based on simulation information. Let $X_{max} = -X_{min}$. The range of each fuzzy variable is normalized between -1 and +1 by introducing a scaling factor to represent the actual signal. The scaling factors are then optimized to minimize the summation of the square error of the speed deviation signal (El-Metwally and Malik, 1993).

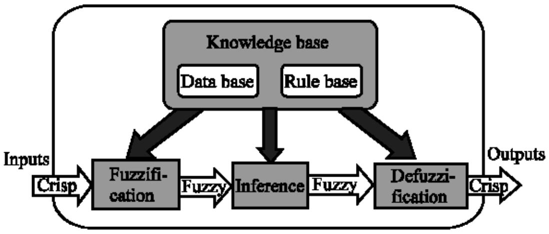


Fig. 1: The basic structure of the fuzzy controller

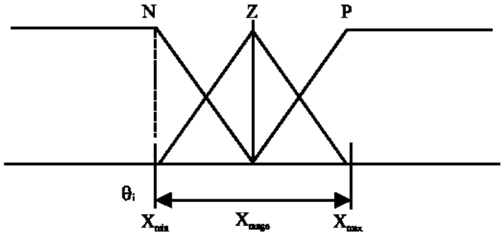


Fig. 2: Fuzzy variable X_i three membership functions

Table 1: Fuzzy logicASS1 rules

	ΔP		
Parameters (Δω)	N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

A symmetrical fuzzy rule set is used to describe the FLPSS1 behavior as shown in Table 1. Each entity in Table 1 shows a rule of the form if antecedent then consequence, e.g., the shaded rule in Table 1 is if Δω is N and ΔP is P then U_{PSS} is Z.

Symmetrical rule base is commonly used among researchers for monotonically increasing systems (Sivanandam *et al.*, 2007).

The activation of the ith rule consequent is a scalar value (ω_i) which is equal to the product of the two antecedent conjunction values. Using the center of gravity defuzzification method, the appropriate crisp control is then generated (Malik and El-Metwally, 1998).

Let $\theta_1,\ldots,\theta_M$ show the centroids of M membership functions that are assigned to U_{PSS}. Thus for M rules, the output of the controller is (Kosko, 1997):

$$U_{PSS} = \frac{\sum_{i=1}^{M} \omega_i \theta_i}{\sum_{i=1}^{M} \omega_i} = \theta^T \zeta \tag{1}$$

Where:

$$\zeta = [\zeta_1,\ldots,\zeta_M]^T, \zeta_i = \frac{\omega_i}{\sum_{k=1}^{M} \omega_k}, \theta^T = [\theta_1,\ldots,\theta_M]$$

The strength of the ith rule is ω_i. It is calculated based on interpreting the 'and' conjunction as a product of the membership values corresponding to the measured values of $\Delta\omega$ and ΔP. For example, the rule strength of the shaded rule in Table 1 is given by:

$$\omega_i = \mu_N(\Delta\omega) \times \mu_P(\Delta P) \tag{2}$$

where, μ_N and μ are the membership functions corresponding to the fuzzy sets N and P, respectively. In standard fuzzy systems, the values $\theta_1, ..,\theta_M$ are set once and kept fixed afterwards. One way to set $\theta_1,\ldots,\theta_M$ is to get the help of an expert in power system stabilization. The other alternative is to use Table 1 that can serve as a generic rule base for a lead (or PD) compensator (Kosko, 1997). Consider Table 1 and assume the range of the control signal U_{PSS} is normalized, i.e., $U_{PSS} \in [-1, 1]$. Let also the membership functions be equally spaced. Then, the membership functions N, Z and P will have their centeroids at -1, 0 and 1, respectively.

In order to show the improvement of the proposed FLPSS1 over the conventional PSS, a 49 rule fuzzy PSS (FLPSS2) is introduced.

Let the letters N, Z and P stand for the linguistic values negative, zero and positive, respectively. Also, let the letters B, M and S stand for big, medium and small, respectively.

Each of the FLPSS2 input and output fuzzy variables is assigned 7 linguistic values varying from Negative Big (NB) to Positive Big (PB). Each linguistic value is associated with a membership function to form a set of seven normalized and symmetrical membership functions for each fuzzy variable as shown in Fig. 3. Let $X_{max} = -X_{min}$.

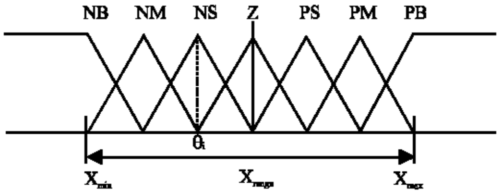


Fig. 3: Fuzzy variable X_i seven membership functions

Table 2: Fuzzy-logicPSS2 rules

	ΔP						
Parameters ($\Delta\omega$)	NB	NM	NS	Z	PS	PM	PB
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

The range of each fuzzy variable is normalized between -1 and +1 by introducing a scaling factor to represent the actual signal.

Consider Table 2 and assume the range of the control signal U_{PSS} is normalized, i.e., $U_{PSS} \in [-1, 1]$. Let also the membership functions be equally spaced. Then, the membership functions NB, NM, NS, Z, PS, PM and PB will have their centeroids at −1, −2/3, −1/3, 0, 1/3, 2/3 and 1, respectively.

RESULTS AND DISCUSSION

In this study, researchers will investigate the performance of the proposed FLPSS as it is applied to both single machine infinite bus and multi-machine models. The purpose of the wind turbine driving a 3-phase synchronous generator connected to a large power system model is to shows that the proposed FLPSS supersedes a conventional PSS. The success of the proposed FLPSS with the single machine infinite bus case motivates us to test its capability on the wind energy distributed generation based multi-machine model. Simulation results of a 5-bus three machine system are included to confirm that the proposed FLPSS is capable of damping power system swing mode oscillations that follow a large disturbance.

Application to the single machine infinite bus model: A non-linear power system model that consists of a wind turbine driving a 3-phase synchronous generator connected to a large power system through a double circuit transmission line is chosen for simulation studies. The system including a wind turbine a synchronous generator and an automatic voltage regulator is described.

Model equations and details are shown in the Appendix 2, 3. A schematic diagram representation of the power system is shown in Fig. 4.

For a comparison purpose, the system is configured to switch between different controllers. In order to show the improvement of the proposed FLPSS over the conventional PSS, two different FLPSSs are used, a 9-rule fuzzy PSS (FLPSS1) and a 49-rule fuzzy PSS (FLPSS2). To investigate the power system performance, two classes of disturbances are studied. These classes are chosen to represent the large as well as small power system disturbances. For fair comparison, the magnitude of the stabilizing signal of all stabilizers is limited to ±0.1 pu. Simulation results are shown in Fig. 5-9.

Response to torque disturbance: To compare the performance of the proposed FLPSS to the CPSS at small disturbances the system is subjected to a series of disturbance an increase by 25% after 0.5 sec then a decrease by 25% after 5 sec in input torque. The study is performed at two different loads and operating conditions. The results are shown in Fig. 5 and 6. In Fig. 5, the FLPSS2 damps the oscillation faster than the FLPSS1. The performance of the fuzzy logic power system stabilizer FLPSS2 is close to that of the FLPSS1 on the expense of a big rule base. In Fig. 6, the disturbance occurs while one of the two transmission lines is out of service and the system supplies half the full load. Figure 6 shows that the

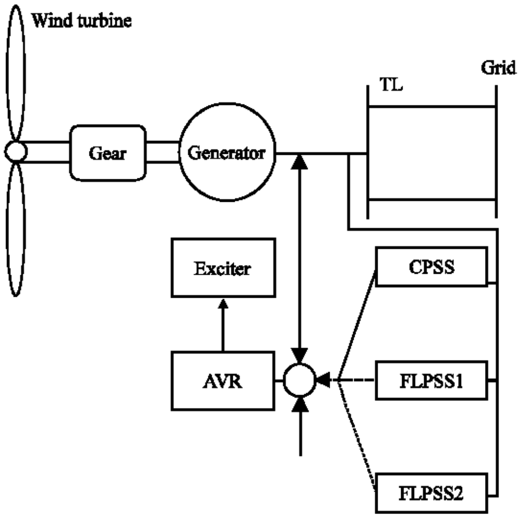


Fig. 4: Schematic diagram of the power system model

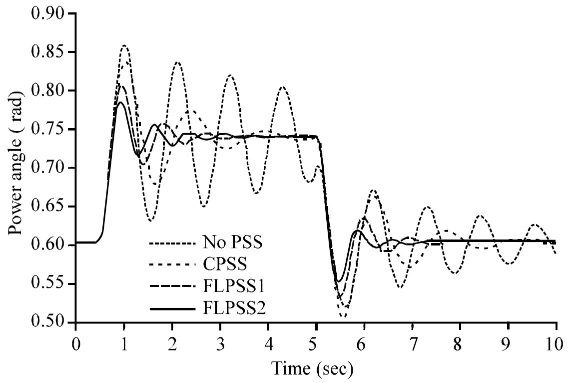


Fig. 5: Response to a 0.25 pu input torque disturbance (p = 0.9, pf = 0.9 lag)

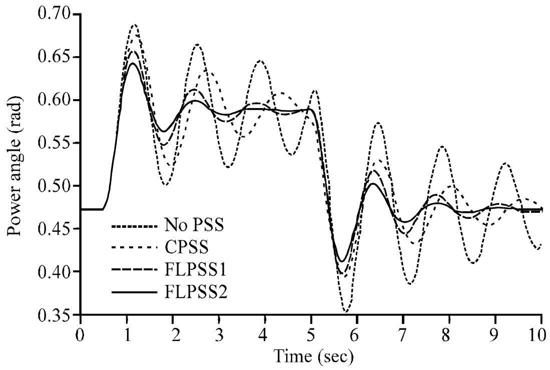


Fig. 6: Response to a 0.1 pu input torque disturbance while one line is out of service (x_{tl} = 0.5, p = 0.5 and pf = 0.9 lagging)

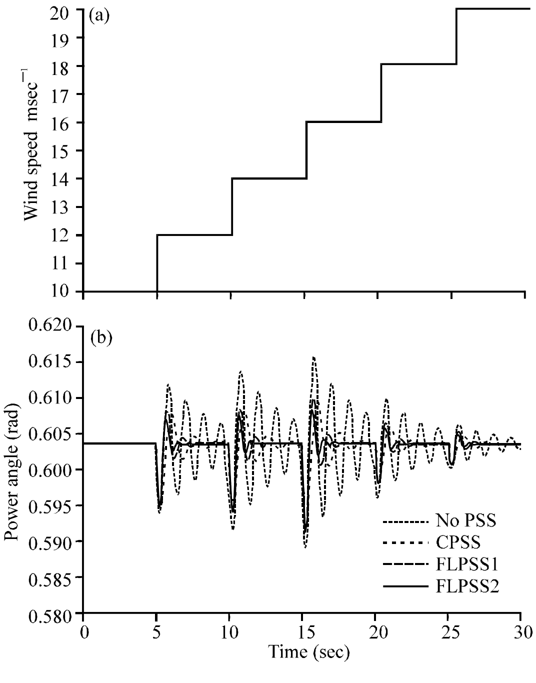


Fig. 7: Response to a step change wind profile (p = 0.9 and pf = 0.9 lag); a) Realistic wind profile; b) Power angle

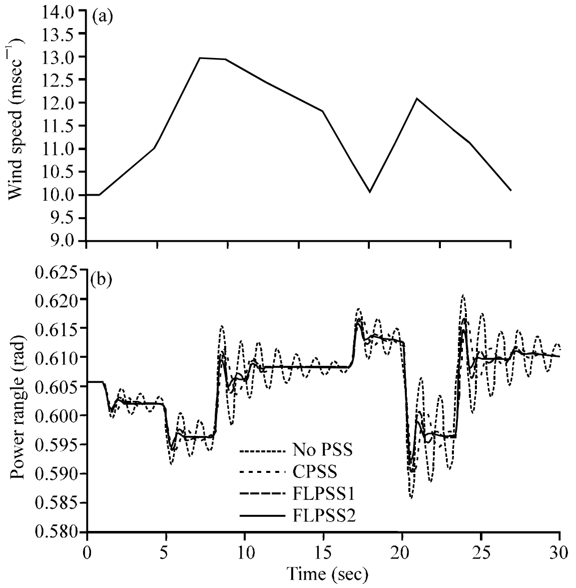


Fig. 8: Response to a realistic wind profile (p = 0.9 and pf = 0.9 lag); a) Step change wind profile; b) Power angle

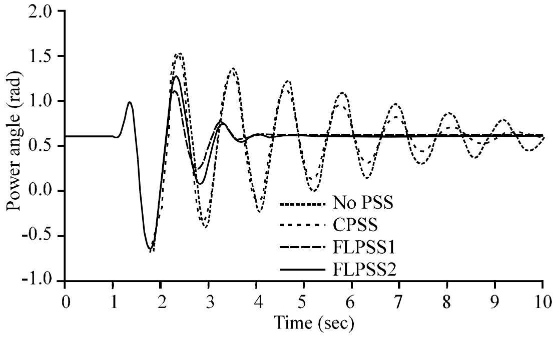


Fig. 9: Response to a 3-phase to ground fault (p = 0.9, pf = 0.9 lag)

damping capability of CPSS is reduced as the loading and operating conditions change. However, the FLPSS1 and FLPSS2 are able to cope with the new conditions.

Response to wind disturbance: To test the effectiveness of the system equipped with the proposed controller, two wind profiles are tested; a step change wind profile and a realistic wind profile. The time responses are shown in Fig. 7 and 8. All controllers show good responses. However, FLPSS1 and FLPSS2 are faster in damping power system oscillations with lower over shooting.

Response to large disturbances: To illustrate the response to a large disturbance, the power system is exposed to a 3-phase to ground fault occurred at the machine terminals at t = 1 sec, for 300 m sec. The system is operating at power of 0.9 pu and 0.9 pf lagging (almost full load) at the time of disturbance. Figure 9 shows the responses of CPSS, FLPSS1 and FLPSS2. During the first swing, all controllers have comparable performance since the magnitude of the stabilizing signal is saturated at 0.1 pu. Afterwards, the damping improvement achieved by the FLPSS is evident.

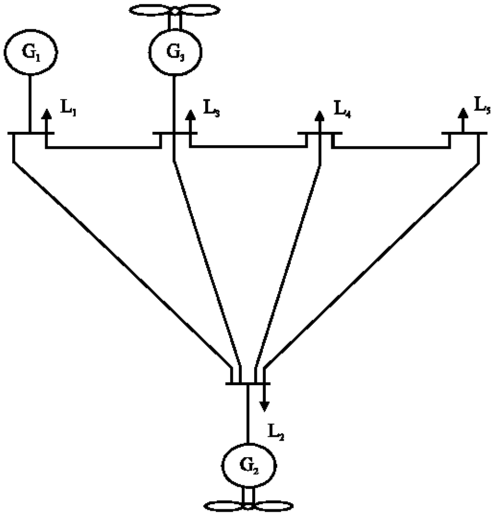


Fig. 10: Schematic diagram of a 5-bus three-machine power system

Using a 9-rule stabilizer the FLPSS1 achieves a significantly fast damping while the CPSS fails. If the rule base of the standard fuzzy PSS is increased to 49-rules (FLPSS2) an acceptable damping is achieved. Still the FLPSS has better performance.

Application to the multi-machine model: The capability of the proposed stabilizer in damping the electromechanical oscillations encountered in multi machine systems is investigated in this study. Figure 10 shows a three machine 5-bus power system. The multi-machine system is comprising of two wind power plants and diesel power plant connected to a large power system. Each machine is represented by its 7th order model and is equipped with an AVR and a governor. The local loads are denoted by L_1-L_5 where the subscript showes the bus number as well. Static loads are assumed however the stator transient is considered in the generation and network models. The loads and the network parameters are showen in Appendix 4. Each generator is equipped with a FLPSS designed as explained in the previous study. It is assumed that a 3-phase to ground fault occurs at the terminals of the machine G_1. The fault starts after 1 sec and lasts for 100 m sec. Figure 11 shows the response of the relative

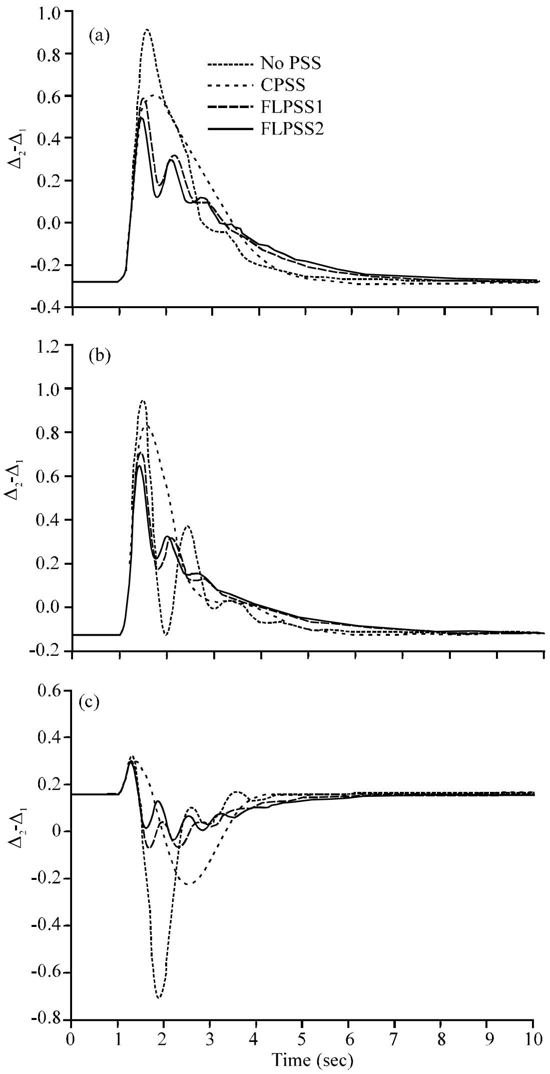


Fig. 11: Time response in rad of the relative power angles when the machine at bus 1 undergoes a 3-phase to ground fault: a) Relative power angle between machine at bus 2 and 1; b) Relative power angle between machine at bus 3 and 1; c) Relative power angle between machine at bus 3 and 2

rotor angles for the three machines. In general, the generators in multi machines systems oscillate in multi mode oscillations namely, common mode in which the machines oscillate in unison and the inter modes in which the machines oscillate with respect to each other as shown in Fig. 11. It is evident that the proposed controller is capable of dealing with oscillations with multiple frequencies that occur in the case of multi-machine systems. Figure 11 also compares the performance of the FLPSS and the CPSS. It is clear that the FLPSS has better damping performance. From the design point of view, rules table eases the tuning burden of the PSS. This becomes evident as the number of the PSS increases in the network.

It is evident from the aforementioned results that the proposed fuzzy logic power system stabilizer substantially improve the damping of the generators oscillations. Increasing the rule size of the controller allows it to act effectively at different operating conditions following small and large disturbances. On the contrary, a conventional power system exhibits deterioration in the damping capability as the operating condition changes. It may even fail in damping large oscillations. The performance of the fuzzy logic stabilizer can be improved on the expense of using a significantly larger rule base. Compared to the CPSS, the extra tuning effort in the proposed FLPSS is limited to the choice of the input and output gains. The objective here has been to demonstrate the advantage of adding the FLPSS to power system. Researchers summarize the benefits of the proposed scheme as:

- It provides a generic rule base generation mechanism
- The fixed rule base structure feature of the controller significantly reduces the computational effort as compared to other classical control schemes
- It reduces the computational time. This results in a reduction of low-level implementation (micro-controllers) which are still in need for compact size code and data for efficient execution and low price. This is valuable for commercial reasons
- Tuning a conventional PSS is very tedious in the multi-machine case. The proposed controller makes tuning feasible in the multi-machine case

CONCLUSION

Fuzzy logic control can be seen as a modular way for defining nonlinear controllers which is much more appropriate to non-linear systems as the case in power system stabilization problems. In this research, it is shown that the FLPSS performance can significantly improve the power system performance. Increasing the rule size has allowed the FLPSS to perform satisfactorily over a wide range of operating conditions. The FLPSS supersedes a conventional PSS since they can benefit from domain expert information to achieve better performance. This research has introduced the concept of fuzzy power system stabilizers for wind power plants. Computer simulations have been used to investigate the capability of the proposed FLPSS. A superior performance has been confirmed over a wide range of operating conditions. It has been shown that a conventional PSS would have needed more tuning effort while the proposed FLPSS has utilized less effort only to yield a comparable performance. This has been due to the fixed rule base capability of the FLPSS. Such good performance has been achieved for multi-machine systems as well.

The FLPSS is one of the recently proposed PSSs that utilize the artificial intelligence. Guided by the power of the fixed rule base control structure it is meant to enhance the dynamic performance of power systems under transient conditions. Fuzzy logic provides an easily understood AI-based design for a PSS. Increasing rule size is necessary to guarantee a good stabilizer performance. Thus, FLPSS is a proper combination of artificial intelligence and power system engineers experience. The effectiveness of the proposed FLPSS is proved through simulations studies and comparison with CPSS.

APPENDICES

Appendix 1: The generating unit is modeled by seven 1st-order nonlinear differential equations as follow:

$$\frac{d\lambda_d}{dt} = e_d + r_a i_d + \omega_0 \omega \lambda_q$$

$$\frac{d\lambda_q}{dt} = e_q + r_a i_q + \omega_0 \omega \lambda_d$$

$$\frac{d\lambda_f}{dt} = e_f - r_f i_f$$

$$\frac{d\lambda_{kd}}{dt} = -r_{kd}\, i_{kd}$$

$$\frac{d\lambda_{kq}}{dt} = -r_{kq}\, i_{kq}$$

$$\frac{d\delta}{dt} = \omega_0 (\omega - 1)$$

$$\frac{d\omega}{dt} = \frac{1}{2H}\left(T_m - T_e + k_d \frac{d\delta}{dt} \right)$$

Machine parameters in pu: $r_a = 0.007$, $H = 10$, $r_f = 0.00089$, $r_{kd} = 0.023$, $r_{kq} = 0.023$, $k_d = 0$, $x_d = 1.24$, $x_f = 1.33$, $x_{kd} = 1.15$, $x_{md} = 1.126$, $x_q = 0.743$, $x_{kq} = 0.652$, $x_{mq} = 0.626$, $x_{TL} = 0.25$. The base power is 100 MVA.

Where:
λ_d = The direct-axis flux linkage
λ_q = The quadrature-axis flux linkage
λ_f = The field flux
λ_{kd} = The damper winding direct-axis flux linkage
λ_{kq} = The damper winding quadrature-axis flux linkage
e_d = The direct axis emf.
e_q = The quadrature axis emf
i_{kq} = The damper winding quadrature-axis current
i_{kd} = The damper winding direct-axis current
i_f = The field current
δ = The power angle
ω_0 = The synchronous speed
ω = The machine speed
T_m = The mechanical torque and
T_e = The electric torque

Appendix 2: The wind turbine unit is modeled as:

$$P_m = \frac{1}{2} \rho A c_p (\lambda, \beta) v^3$$

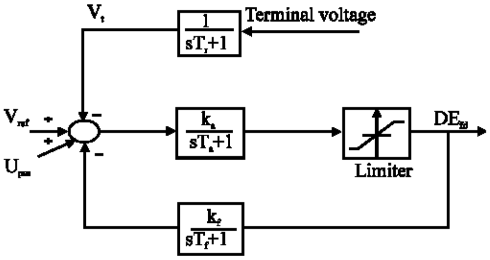
Where:
P_m = The mechanical output power of the turbine (W)
c_p = The performance coefficient of the turbine
ρ = The air density (kg m^{-3})
A = The turbine swept area (m^2)
v_{wind} = The wind speed (m sec^{-1})
λ = The tip speed ratio of the rotor blade tip speed to wind speed
β = The blade pitch angle (deg)

$$c_p(\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda_i} - c_3 \beta - c_4 \right) e^{\frac{-c_5}{\lambda_i}} + c_6 \lambda$$

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

where, c_1-c_6 are the turbine constants.

Appendix 3: The AVR wind turbine unit is modeled as:



$T_r = 0.04$, $k_a = 200$, $T_a = 0.05$, $k_f = 1$, $T_f = 0$

Appendix 4: Parameters of the multi-machine system

Bus code p-q	Impedance Z_{pq} in pu	Line charging $y_{pq}/2$ in pu
1-2	0.02+j0.060	0.0+j0.030
1-3	0.08+j0.024	0.0+j0.025
2-3	0.06+j0.018	0.0+j0.020
2-4	0.06+j0.018	0.0+j0.020
2-5	0.04+j0.120	0.0+j0.150
3-4	0.01+j0.030	0.0+j0.050
4-5	0.08+j0.240	0.0+j0.025

The loads in MVA at the power system buses are: $L_1 = 0+j0$, $L_2 = 20+j10$, $L_3 = 45+j15$, $L_4 = 40+j5$, $L_5 = 60+j10$

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