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Fuzzy-based Coordinated Control Design for AVR and PSS in Multi-machine Power Systems

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***Abstract*— This paper presents the performance of intelligent fuzzy-based coordinated control for Automatic Voltage Regulator (AVR) and Power System Stabilizer (PSS) to prevent losing synchronism after a major sudden fault and to achieve appropriate post-fault voltage level in multi-machine power systems. The AVR and PSS gains can adaptively change to guarantee the power system stability after faults. To change in AVR and PSS gains at least one significant generator in each area is equipped with a fuzzy logic unit. The fuzzy logic unit accepts normalized deviation of terminal voltage and normalized phase difference as inputs and generates the favorable gains for AVR and PSS. The work describes the construction of appropriate fuzzy membership functions and rules for best tuning of gains. The proposed fuzzy control methodology has been applied to 11-bus 4-generator power system test case. Simulation results illustrate the effectiveness and robustness of this fuzzy-based coordinated control.**

***Index Terms*— Power system stability, voltage regulation, Fuzzy control, AVR, PSS, normalize deviation.**

I. INTRODUCTION

Multi-machine power systems ever threatened by different disturbances, this problem may cause the instability or change in voltage level of the generators [1]. Instability and emergency condition in the Europe and Canada's power system led to a major blackout surround these countries [2]. Early, the generators utilized Automatic Voltage Regulator (AVR) merely. With appearance of frequency and voltage oscillations power systems equipped with Power System Stabilizers (PSSs) as the second controller to enhance the oscillatory stability. The AVR and PSS are installed on the generators that improve of the rotor angle stability consisting transient and small signal stability and optimal tuning at the terminal voltage is the target of this installation [1], [3].

It is noteworthy that after a fault condition in the power system, a high-gain fast-response AVR while improves the large-signal transient stability it has detrimental effect on oscillation stability and has a converse effect of the PSS on transient stability while it improves the small signal oscillatory stability [4]. This is because of that, the AVR and PSS controllers generally designed for the nominal operating point, and for the fault situation it is necessary to have a coordination between two controllers .

In the past decades, a lot of papers investigated the transient and oscillatory stability enhancement with and without coordinated AVR-PSS [5]-[10]. To stability improvement and optimal control in power system several papers have changed the conventional structure of the system [5], [6]. The known framework for these changing structures are Internal Model Control (IMC) and Decentralized Four Loops Regulator (DFLR). Multi-machine power systems have complex models that this is reduced the usage of these methods. With the conventional AVR-PSS and an additional optimal static gain vector, [7] has attempted to gain robust performance of excitation system. The optimal gain vector has used the feedback signals including terminal voltage, active power and machine speed. In order to optimal tuning of gains, the problem is formulated via an H∞ static output feedback (H∞-SOF) control technique. Adding an extra loop can be troublesome with attention to antiquity of AVR-PSS usage as the only local controllers. A Proportional Integral Differential (PID) controller for power system is designed in [8]. Since the PID gets feedback from machine speed it can not regulates the generator voltage in appropriate level. Bode frequency response with a step-by-step algorithm is addressed in [9] to create a trade-off between AVR and PSS. The bode frequency responses are suitable for small signal stability analysis. A control algorithm that is employed a new comprehensive criterion for the coordinated AVR-PSS is proposed in [10] and then a control strategy is designed based on the switching technique and negative feedback. The control strategy is not designed based on a specific control method.

Although, a large number of techniques have been employed in power systems, intelligent fuzzy logic is a powerful tool in meeting challenging problems for stability of power systems. Because fuzzy logic is a technique which can handle imprecise problems without considering complexity, nonlinearity and mathematical model of units [11], [12]. Many researchers have suggested fuzzy logic to design PSS [13]-[16]. These papers only considered small signal stability or damping of low-frequency oscillations. [17], [18] have proposed fuzzy logic scheme for both aims (enhancement of stability and voltage regulation) in power system. Using a transient controller and a voltage regulator that obtained using direct feedback linearization method and with a fuzzy logic

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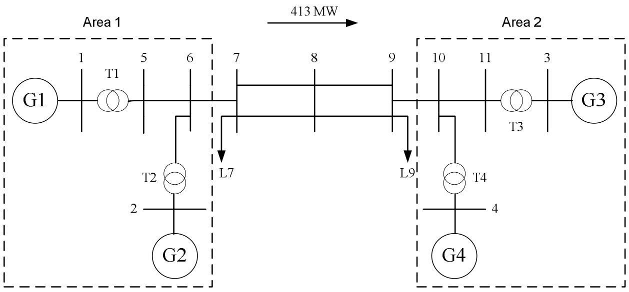


Fig. 1. Test case power system

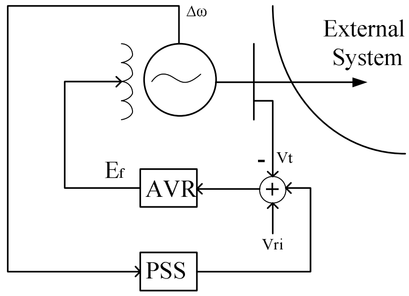


Fig. 2. Generator with conventional AVR and PSS

unit in [17] power system has better performance. Fuzzy controller accepts the voltage and speed deviations as input signals and the output of fuzzy controller (μ) gives the weightage of transient controller and its complement (1-μ) gives the weightage of voltage controller. As regards, voltage and speed of generators in power systems do not deviate at specified intervals.

In this paper, a fuzzy-based coordinated control scheme is proposed for fine tuning of AVR-PSS gains. The AVR and PSS gains can change in acceptable intervals to guarantee the power system stability and optimal voltage regulation after faults. To change the conventional AVR-PSS gains, a significant generator in each area has equipped with a fuzzy logic unit. This fuzzy unit accepts normalized terminal voltage deviation and normalized phase difference as its input signals and generates the favorable gains for the AVR and PSS controllers. The work describes the construction of appropriate fuzzy membership functions and rules for best tuning of gains. The 11-bus 4-generator as a practical system for dynamic studies is selected to illustrate the effectiveness and robustness of this fuzzy-based coordinated control methodology. The simulations have been implemented with a sever fault in the system.

The paper is organized in five sections. The details of simulated power system with 11-bus 4-generator is discussed in section II. Section III describes the fuzzy-based coordinated control methodology. In section IV simulation results are explained and finally section V concludes the paper.

II. TEST SYSTEM

Simulated power system is a 11-bus 2-area power system that each area has 2 generators. The details about this system can be found in [3]. Fig. 1 indicates this test case power system. All generators have AVR and PSS controllers. Fig. 2 shows the generator with these local controllers. As it is visible in this schematic figure, AVR and PSS, enhance the power system stability and voltage regulation with an unit signal. This represents that, why coordination between these two controllers is necessary.

The AVRs have first order transfer functions given by:

$$\mathrm{AVR(s)} = \frac{200}{0.01s+1}$$

The PSSs have conventional form with two lead-lag transfer functions as they formulated by :

$$\mathrm{PSS(s)} = 30 \times \frac{10s}{10s+1} \times \frac{0.05s+1}{0.02s+1} \times \frac{3s+1}{5.4s+1}$$

III. FUZZY-BASED COORDINATED CONTROL

Fuzzy logic is an artificial method that independent from the complexity, nonlinearity and mathematical models of study units. Generally, a controller design based on fuzzy logic for a dynamical system involves the following four main steps [12]:

Step 1) Understanding of the system dynamic behavior characteristics. Define the states and input/output control variables and their variation ranges.

Step 2) Identify appropriate fuzzy sets and membership functions. Create the degree of fuzzy membership function for each input/output variable and complete fuzzification.

Step 3) Define a suitable inference engine. Construct the fuzzy rule base, using the control rules that the system will operate under. Decide how the action will be executed by assigning strengths to the rules.

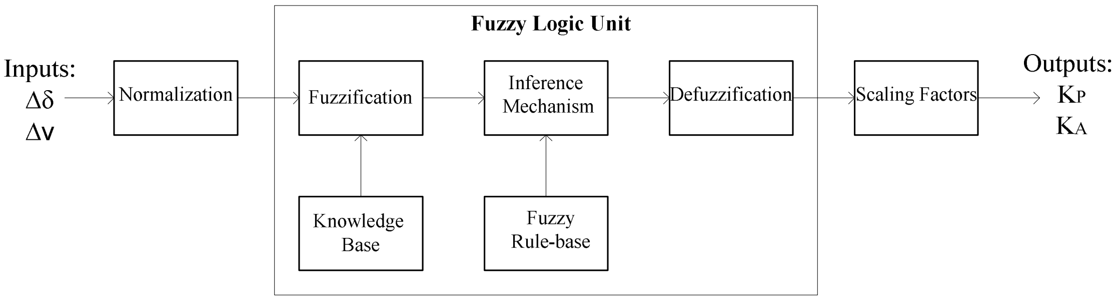


Fig. 3. A step-by-step scheme for fuzzy controller

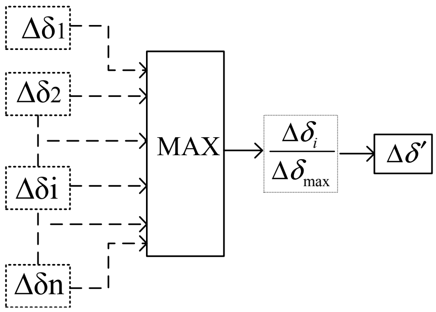


Fig. 4. The normalization method

Step 4) Determine defuzzification method. Combine the rules and defuzzify the output.

In this paper, fuzzy logic controller generates the acceptable gains K_P and K_A for conventional AVR and PSS following a fault to enhancement the power system stability and suitable post-fault voltage level. In other word, we have two local controllers (AVR-PSS) and a fuzzy logic unit for best tuning of the two controller gains. Fig. 3 depicts a step-by-step scheme of the fuzzy controller design. The normalization and scaling factor blocks are not fuzzy components. These two blocks have been designed for best performance of fuzzy logic unit. As shown, the fuzzy unit contains four major components: fuzzification, fuzzy rule-base, inference mechanism and defuzzification.

A. Input Signals and Normalization

There are a lot of signals in power system that can be select as the input signals for fuzzy controller. About the voltage regulation it is better to choose the terminal voltage as one of the inputs. But for guarantee the synchronism in power system, terminal voltage can not meet a satisfy performance merely. The angle deviation can be used as the second signal input for stability enhancement. Therefore fuzzy controller has two inputs: terminal voltage deviation and phase difference.

On the other hands, at the power systems, with fault occurrence the terminal voltage deviation and phase difference maybe unlimited. To limit these deviations, a normalization method is applied. A general scheme for normalization of

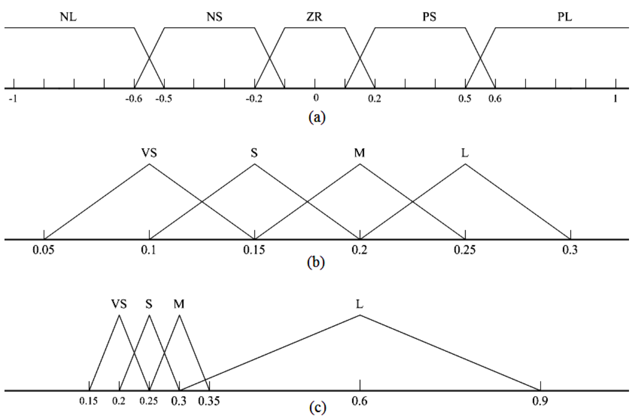


Fig. 5. Membership functions for; a) input signals, b) output K_A and c) output K_P

Table I.

Fuzzy Rule Base for, a) PSS gain and b) AVR gain

(a)

K_P		$\Delta V'$ NL	NS	ZR	PS	PL
$\Delta\delta'$	NL	VS	VS	VS	VS	S
	NS	S	S	S	M	M
	ZR	S	S	M	M	M
	PS	S	S	M	M	M
	PL	M	L	L	L	L

(b)

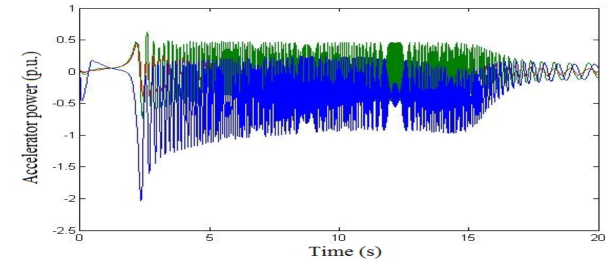
K_A		$\Delta V'$ NL	NS	ZR	PS	PL
$\Delta\delta'$	NL	VS	S	VS	VS	S
	NS	VS	S	S	VS	L
	ZR	VS	S	S	S	L
	PS	VS	S	S	S	M
	PL	S	M	M	M	L

phase difference is illustrated in Fig. 4. The same method is used for voltage deviation normalization. $\Delta\delta'_I$ and $\Delta V'_I$ demonstrate the normalized phase difference and terminal voltage deviation. The $\Delta\delta'_I$ and $\Delta V'_I$ can change in [-1, 1] for all the generators in system.

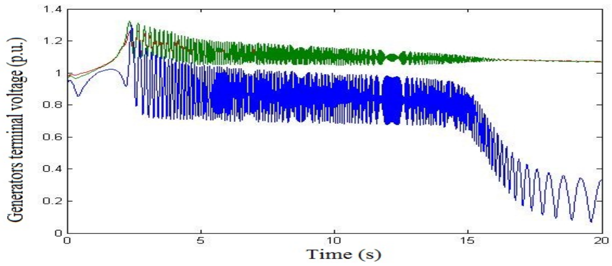
B. Fuzzification

In real world, many phenomena and measures are not crisp and deterministic. Fuzzification plays an important role in dealing with uncertain information, which might be objective or subjective in nature. The fuzzification block in the fuzzy controller represents the process of making crisp quantity into fuzzy. In fact, the fuzzifier converts the crisp input to a linguistic variable using the membership functions stored in the fuzzy knowledge base. Fuzzines in a fuzzy set is characterized by the membership functions. Using suitable membership functions, the range of input and output variables are assigned with linguistic variables. These variables transform the numerical values of the input of the fuzzy controller to fuzzy quantities. These linguistic variables specify quality of the control.

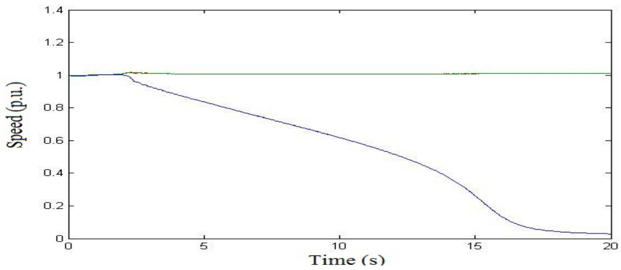
Here the membership functions corresponding to the input variables are arranged as Negative Large (NL), Negative Small (NS), Zero (ZR), Positive Small (PS) and Positive Large (PL), and for the output variables they are arranged as Very Small (VS), Small (S), Medium (M), Large (L). The membership functions for input and output variables are demonstrated in Fig. 5. They have arranged based on triangular and trapezoid, which they are more common membership functions to use in fuzzy control systems.



(a)

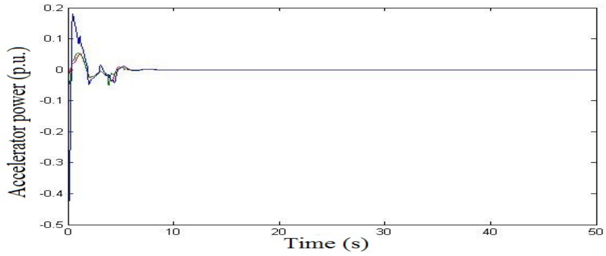


(b)

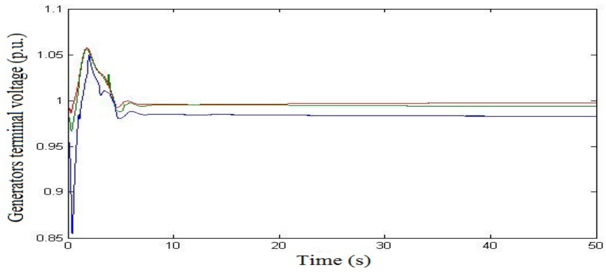


(c)

Fig. 6. Time domain results after outage of generator 3 without fuzzy



(a)



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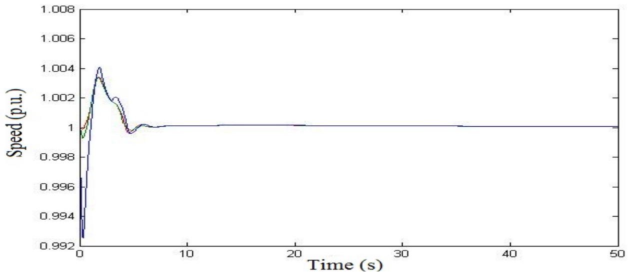

(c)

Fig. 7. Time domain results after outage of generator 3 with fuzzy unit

C. Fuzzy-Rule Base and Inference Mechanism

Knowledge rule base consists of information storage for linguistic variables definitions (database), and fuzzy rules (control base). The concepts associated with a database are used to characterize fuzzy control rules and a fuzzy data manipulation in fuzzy logic controller. A lookup table is made based on discrete universes that defines the output of a controller for all possible combinations of the input signals. A fuzzy system is characterized by a set of linguistic statements in the form of "IF-THEN" rules. Fuzzy conditional statements make the rules or the rule set of the fuzzy controller. Finally, the inference engine uses the IF-THEN rules to convert the fuzzy input to the fuzzy output.

Fuzzy inference is the kernel of a fuzzy logic system. The performed fuzzy rules are given in Table I . The antecedent part of each rule are composed by using AND function. Here, Mamdani fuzzy inference system is also used.

D. Defuzzification and Scaling Factors

Defuzzification converts the fuzzy output of the inference engine to crisp using membership functions analogous to the ones used by the fuzzification. The centroid method has been used for defuzzification. With attention to output intervals, the scaling factors are necessary to provide acceptable gains for AVR and PSS controllers.

IV. Simulation Results

The efficiency of the fuzzy logic based coordinated control for AVR-PSS is tested on 11-bus test system. As described in section II, the power system has two areas with two generators in each area. The nominal system is operating with area 1 exporting 413 MW to area 2. For each generator in this power system, AVR and PSS have been activated. The effective generator in each area has been equipped with fuzzy unit. Generator 2 in area I is the swing bus in the system and generator 4 at the area II has more power rate. These two generators (2,4) have been selected as the effective generators in the power system. The time domain simulation responses illustrate the efficiency and robustness of the fuzzy-based coordinated controller. The fuzzy control strategy has been implemented in the system after one second after faults. This is so because of that, the time horizon for transient instability is about 3-5 seconds and this time horizon for small signal instability is about 10-20 seconds. Behavior of the power system after outage of generator 3 is investigated as the fault scenario. Outage of generator can be account a sever fault in the power systems. Fig. 6 shows the time domain responses of the generators outputs without fuzzy unit after outage of generator number 3. Regarding the obtained speed (ω) diagram, the power system is lost its synchronism, and two areas have been separated. Because of that, generator number 4 can not supply the whole load in the area 2 and voltage collapse is occurred in this area. Generators have oscillations in accelerator power after fault. So we have instability in the system. After adding the fuzzy logic unit to the AVR and PSS in generators 2 and 4 the time domain results consists of voltage, speed and accelerator power are shown in Fig. 7. The fuzzy controllers prevent losing synchronism in the system and terminal voltage is returned to the acceptable level.

V. Conclusion

The AVR and PSS are the local controllers that ensure the power system stability and voltage regulation for nominal operating point of the system. For appropriate performance after faults it is need to have a coordination between these two controllers.

This paper suggests a fuzzy-based coordinated control strategy for best tuning of AVR-PSS gains after faults. The fuzzy unit accepts normalized terminal voltage deviation and phase difference as its input signals and generates the AVR and PSS gains in acceptable intervals. Performance of the fuzzy control unit with conventional AVR-PSS has been investigated on 11-bus 2-area power system case study that each area has two generators. Generator 2 in area 1 and generator 4 in area 2 were equipped with fuzzy unit. Simulation results illustrate the efficiency and robustness of this fuzzy control strategy in fault situation.

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