Fuzzy logic controller as a power system stabilizer

Jenica Ileana Corcau, Eleonor Stoenescu

Abstract**—** In this paper, the structure of an fuzzy PID controller is presented. The application of the fuzzy logic controller as a power system stabilizer is investigated by means of simulation studies on a single machine infinite bus system. To be successful in implementing fuzzy PID controllers in large applications we must also consider their operating principles. Fuzzy logic controllers are based on empirical control rules. The development of a fuzzy logic based power system stabilizer in order to maintain stability and enhance the closed-loop performance of a power system is described in this paper. A study case for the validation of the proposed tunning mechanism is presented and analyzed with control application for a synchronous generator excitation system. The superior performance of this stabilizer in comparison to the conventional fixed gain stabilizer proves the efficiency of this new PID fuzzy controller.

Keywords**—** adaptive control, fuzzy logic control, PID stabilizer, synchronous generator, transient perturbations.

I. INTRODUCTION

Control algorithms based on fuzzy logic have been implemented in many processes. The application of such control techniques has been motivated by the following reasons: 1) improved robustness over the conventional linear control algorithms; 2) simplified control design for difficult system models; 3) simplified implementation [1], [11], [12].

Low –frequency oscillations are a common problem in large power systems. A power system stabilizer (PSS) can provide an supplementary control signal to the excitation system and/or the speed governor system of the electric generating unit to damp these oscillations.

Due to their flexibility, easy implementation, and low cost, PSSs have been extensively studied and successfully used in power systems for many years.

Most PSSs in use in electric power systems employ the classical linear control theory approach based on a linear model of a fixed configuration of the power system. Such a fixed-parameter PSS, called a conventional PSS (CPSS), is widely used in power systems and has made a great contribution in enhancing power system dynamics [1], [9].

The power system stabilizer (PSS) is used to generate supplementary control signals for the excitation system in order to dampen the low frequency oscillations.

The conventional power system stabilizer is widely used in existing power systems and has contributed to the enhancement of the dynamic stability of power systems.

The parameters of CPSS (Conventional Power System Stabilizer) are determined based on a linearized model of the power system around a nominal operating point where they can provided good performance. Because power systems are highly nonlinear systems, with configurations and parameters that change with time, the CPSS design based on the linearized model of the power systems cannot guarantee its performance in a practical operating environment [2].

To improve the performance of CPSS, numerous techniques have been proposed for their design, such us using intelligent optimization methods (genetic algorithms, neural networks, fuzzy and many other nonlinear control techniques).

It recent years, fuzzy logic control has emerged as a powerful tool and is starting to be used in various power system applications [1], [11], [14].

The application of fuzzy logic control techniques appears to be most suitable one whenever a well-defined control objective cannot specified, the system to be controlled is a complex one, or its exact mathematical model is not available.

Recent research indicates that more emphasis has been placed on the combined usage of fuzzy systems and neural networks [2] [6]-[10].

This paper presents a new power system stabilizer with an adaptive PID fuzzy controller for different operating conditions of the power system. Various simulations have been performed in order to subject it to several types of large disturbances using a single-machine infinite bus power system.

Comparison studies have also been performed between the conventional proportional integral power stabilizers (PSS) and the fuzzy PID. The numerical simulations results clearly demonstrate the superiority of the PID fuzzy in comparison to the CPSS.

II. THE MODEL OF A PROCESS – SYNCHRONOUS GENERATOR

The single machine infinite bus power system (SMIB) model used to evaluate the PID fuzzy controller is presented in figure 1.

The SMIB consists of a synchronous generator, a turbine, a

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governor, an excitation system and a transmission line connected to an infinite bus [3]. The model of the SMIB is built in the Matlab/Simulink software suite.

When a power system under normal load condition suffers a perturbance there is synchronous machine voltage angles rearrangement. If for each perturbance that occurrs, an unbalance is created between the system generation and the load, a new operation point will be established and consequently there will be voltage angle adjustments. The system adjustment to its new operation condition is called “transient period” and the system behavior during this period is called “dynamic performance”.

As a primitive definition, it can be said that the system oscillatory response during the transient period, shortly after the perturbance, is damped and the system goes in a definite time to a new operating condition, so the system is stable. This means that the oscillations are damped, that the system has inherent forces which tend to reduce the oscillations.

The instability in a power system can be shown in different ways, according to its configuration and its mode of operation, but it can be observed without synchronism loss.

The generating unit is modeled by the five first-order differential equations given below [4], [7]

$$\dot{\delta} = \omega - \omega_0, \tag{1}$$

$$\dot{\omega} = \frac{\pi f}{H}\left(T_m - T_e\right), \tag{2}$$

$$T'_{d0}\dot{e}'_q = e_f - (x_d - x'_d)i_d - e'_q, \tag{3}$$

$$T''_{d0}\dot{e}''_q = [e'_q - (x'_d - x''_d)i_d - e''_q] + T''_{d0}\dot{e}'_q, \tag{4}$$

$$T''_{q0}\dot{e}''_d = -(x_q - x''_q)i_q - e''_d. \tag{5}$$

there T_e is electric torque output of the generator.

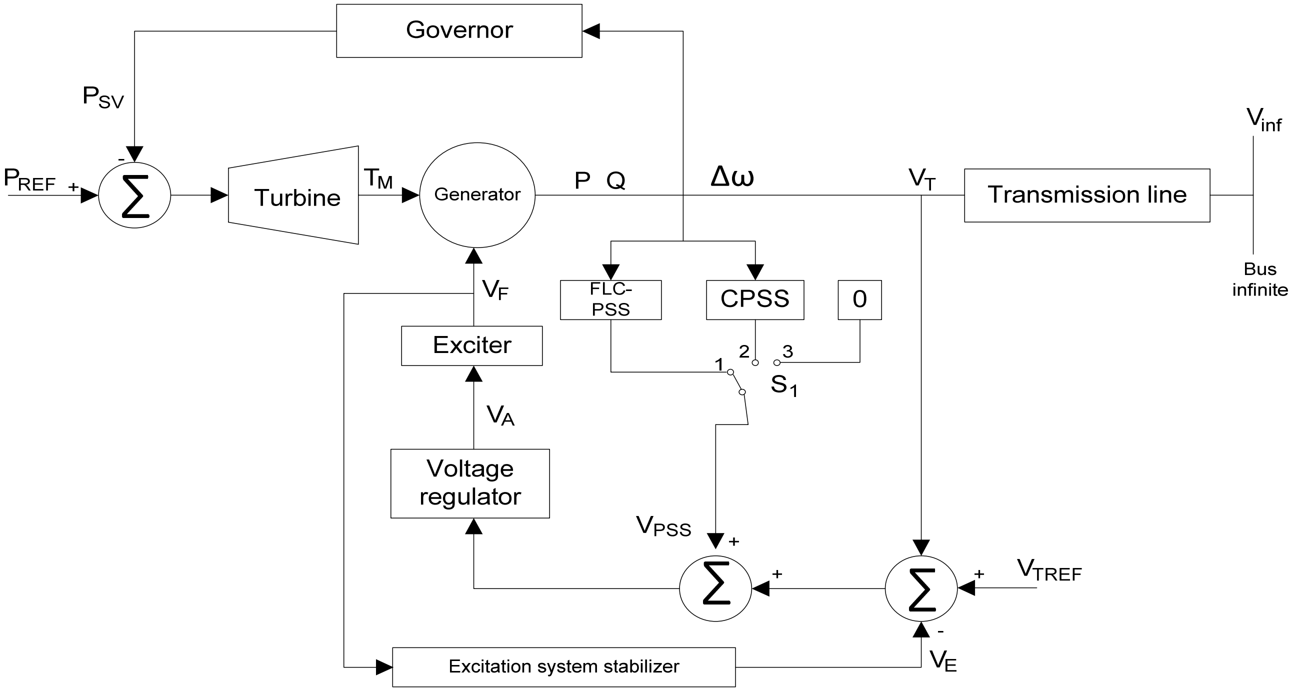


Fig. 1 System model configuration

In figure 1 P_{ref}, is the mechanical power reference, P_{SV}, is the feedback through the governor, T_M, is the turbine output torque, $V_{\inf}$, is the infinite bus voltage, V_{TREF}, is the terminal voltage reference, V_T, is the terminal voltage, V_A, is the voltage regulator output, ΔΩ is the speed deviation, V_{PSS}, is the PSS output, V_F, is field voltage, V_E, is the excitation system stabilizing signal, P, is the power active and Q, is the reactive power at the generator terminal.

The turbine is used to drive the generator and the governor is used to control the speed and the real power. The block diagram of a separately excited turbine and a conventional governor is shown in figure 2.

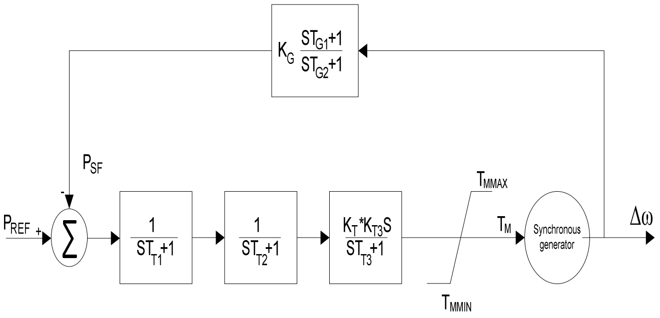


Fig. 2 Block diagram of the turbine and the governor

The block diagram of the excitation system for the generator is presented in figure 3 [2], [5], [15].

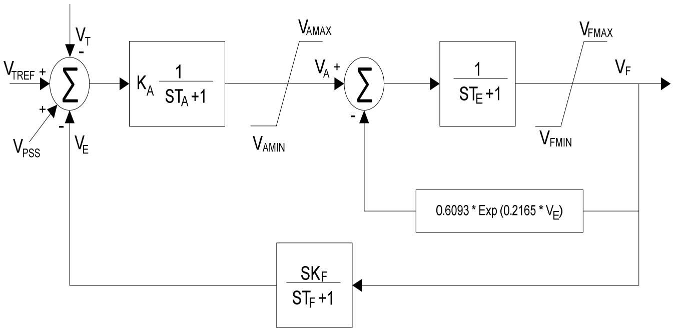


Fig. 3 Block diagram of the excitation system

According to the well-known design method which uses CPSS, the electromechanical oscillations are damped by implementing the PSS as shown in figure 4.

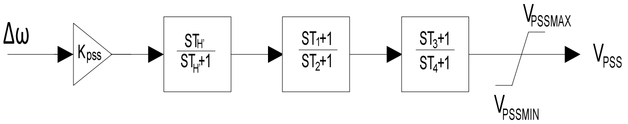


Fig. 4 Block diagram of the conventional power system stabilizer

Automatic devices control the generator’s output in voltage and frequency, in order to keep them constant according to pre-established values.

These automatic devices are:

- Automatic voltage;
- Regulator;
- Governor.

The main objective of the automatic voltage regulator AVR is to control the terminal voltage by adjusting the generators exciter voltage. The AVR must keep track of the generator terminal voltage all the time and under any load condition, working in order to keep the voltage within pre-established limits. Based on this, it can be said that the AVR also controls the reactive power generated and the power factor of the machine once these variables are related to the generator excitation level [15].

The AVR quality influences the voltage level during steady state operation, and also reduce the voltage oscillations during transient periods, affecting the overall system stability.

The parameters for the generator, AVR, excitation system, turbine and governor are given in reference 2. An indirect adaptive neural network based power system stabilizer design is proposed in reference 2.

III. FLC STRUCTURE

In the conventional control, the amount of control is determined in relation to a number of data inputs using a set of equations to express the entire control process. Expressing human experience in the form of a mathematical formula is a very difficult task, if not an impossible one. Fuzzy logic provides a simple tool to interpret this experience into reality.

Fuzzy logic controllers are rule-based controllers. The structure of the FLC resembles that of a knowledge based controller except that the FLC utilizes the principles of the fuzzy set theory in its data representation and its logic. The basic configuration of the FLC can be simply represented in four parts, as shown in figure 5 [17].

- Fuzzification module – the functions of which are first, to read, measure, and scale the control variable (speed, acceleration) and, second, to transform the measured numerical values to the corresponding linguistic (fuzzy variables with appropriate membership values);
- Knowledge base - this includes the definitions of the fuzzy membership functions defined for each control variables and the necessary rules that specify the control goals using linguistic variables;
- Inference mechanism – it should be capable of simulating human decision making and influencing the control actions based on fuzzy logic;
- Defuzzification module – which converts the inferred decision from the linguistic variables back the numerical values.

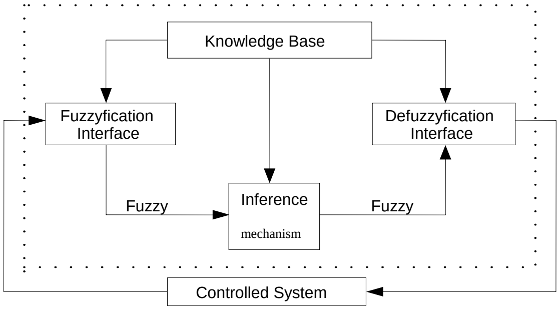


Fig. 5 Schematic diagram of the FLC building blocks

IV. FLC DESIGN

The design process of an FLC may split into the five steps described as:

a. Selection of the control variables

The selection of control variables (controlled inputs and outputs) depends on the nature of the controlled system and the desired output. Usually the output error (*e*) and the rate or derivative of the output (d*e*) are used as controller inputs. Some researchers have also proposed the use of error and the integral of error as an input to the FLC [18].

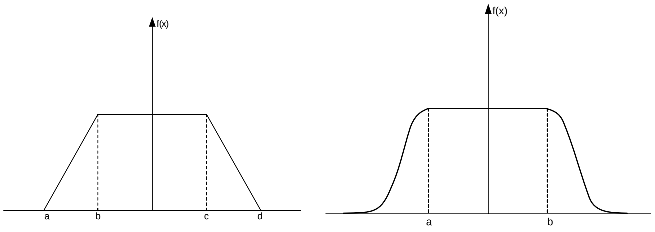
b. Membership function definition

Each of the FLC input signal and output signal, fuzzy variables ($X_j=\{e, de, u\}$), has the real line R as the universe of discourse. In practice, the universe of discourse is restricted to a comparatively small interval [X_{minj}, X_{maxj}]. The universe of discourse of each fuzzy variables can be quantized into a number of overlapping fuzzy sets (linguistic variables).

The number of fuzzy sets for each fuzzy variables varies according to the application. The reasonable number is an odd number (3,5,7…). Increasing the number of fuzzy sets results in a corresponding increase in the number of rules.

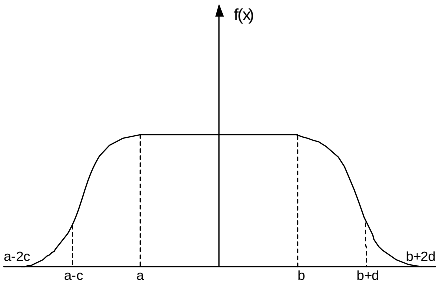
Membership functions can be of a variety of shapes, the most usual being triangular, trapezoidal, singleton or an exponential.

In figure 6 three basic membership functions are presented [17]. The simplest and most efficient form of membership function is the triangular one.



(a) The trapezoidal membership functions

(b) The exponential membership functions



(c) The singleton membership functions
Fig. 6 Three basic membership functions

The main part of the FLC is the Rule Base and the Inference Mechanism. The rule base is normally expressed in a set of Fuzzy Linguistic rules, with each rule triggered with varying belief for support. The ith linguistic control rule can be expressed as:

R_i: If e_i is A_i and de_i is B_i THEN u_i is C_i,

Where A_i and B_i (antecedent), C_i (consequent) are fuzzy variables characterized by fuzzy membership functions.

The set of fuzzy rule for a simple FLC normally can be exprimed as a table as shown in table 1.

TABLE 1 RULE BASE FOR A SIMPLE PI-LIKE FLC TO CALCULATE OUTPUT

de\e	N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

This figure illustrates the fuzzy composition by MAX-MIN principle for two fired rules. Note that the output membership function of each rule is given by the MIN operator whereas the combined fuzzy output is given by the MAX – operator.

The composition operation can be expressed as:

$$\mu_B(u) = SUP_x[MIN(\mu_A(x), \mu_B(x,u))] \tag{6}$$

Where A is the known fuzzy set for the input x and B is the inferred fuzzy set for the output.

In figure 7, there is only one input fuzzy subset (A) for each rule. μ_1 is the minimal membership degree for the input fuzzy subsets (A) of the Rule 1; μ_2 is the minimal membership degree for the input fuzzy subset (A) of the find Rule 2. B_1 and B_2 are the inferred fuzzy subset given by the MIN operator; B is the inferred output fuzzy subset given by the MAX operator.

c. Defuzzification strategy

Defuzzification is a process of converting the FLC inferred control actions from fuzzy vales to crisp values.

This process depends on the output fuzzy set, which is generated from the fired rules.

The performance of the FLC depends very much on the deffuzzification process. This is because the overall performance of the system under control is determined by the controlling signal (the defuzzified output of the FLC) that the system universe [17].

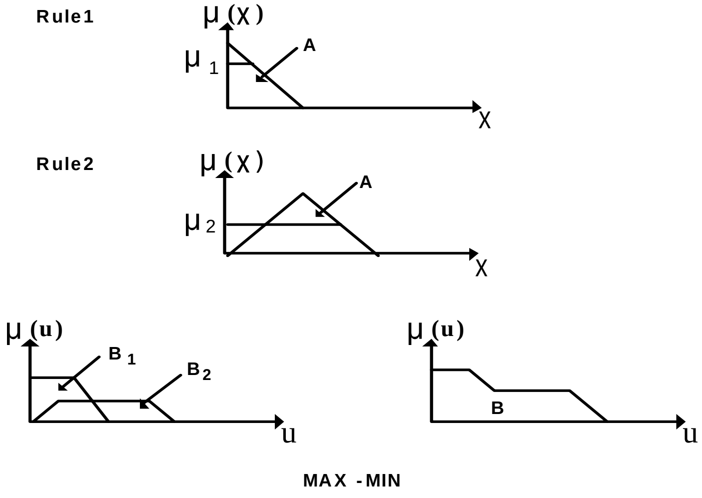


Fig. 7 The MAX – MIN Fuzzy composition method

As mentioned in [17] various defuzzification methods have been proposed to convert the output of the fuzzy controller to a crisp value required by the plant. These methods are: Center of Area (COA), Center of Sum (COS), Height Method (HM), Mean of maxima (MOM), Center of Largest (COLA) and First maxima (FM).

In figure 8 shown how the COA defuzzification operation converts the output of the fuzzy controller to a crisp value required by the plant.

The corresponding algorithms is:

$$U_0 = \frac{\int \omega\mu(\omega)\mathrm{d}\omega}{\int \mu(\omega)\mathrm{d}\omega} \tag{7}$$

Where ω is the output fuzzy variable, the corresponding fuzzy subset is C defined in the universe of discourse W.

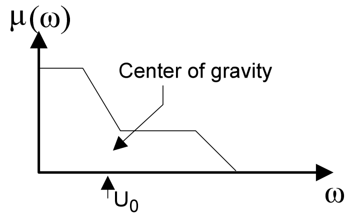


Fig. 8 Graph representation of the defuzzification method

V. ADAPTIVE PID FUZZY CONTROLLER

Controllers based on the fuzzy logic give the linguistic strategies control conversion from expert knowledge in automatic control strategies.

The development of the control system based on fuzzy logic involves the following steps:

- Fuzzification strategy;
- Data base building;
- Rule base elaboration;
- Inference machine elaboration;
- Deffuzification strategy.

In addition, the design of fuzzy logic controller can provide the desirable signal both small and large signal dynamic performance at same time, which is not possible with linear control technique. Therefore, fuzzy logic controller has the ability to improve the robustness of the synchronous generator.

The development of the fuzzy logic approach here is limited to the design and structure of the controller. The input constraints were terminal voltage error and its variations; the output constraint was the increment of the voltage exciter.

The inputs of PID-like FLC are defined as the voltage error $e_u(k)$ and change of error $de_u(k)$. The fuzzy controller ran with the input and output normalized universe [-1, 1].

Fuzzy sets are defined for each input and output variable. There are seven fuzzy levels (LN - large negative, MN - medium negative, SN - small negative, Z - zero, SP - small positive, MP - medium positive, LP - large positive) [7]. The membership functions for input and output variable are triangular. The min - max method inference engine is used; the defuzzify method used in this FLC is center of area. The complete set of control rules is shown in table 2.

TABLE 2. CONTROL OUTPUTS

de/e	LN	MN	SN	Z	SP	MP	LP
LN	LP	LP	LP	MP	MP	SP	Z
MN	LP	MP	MP	MP	SP	Z	SN
SN	LP	MP	SP	SP	Z	SN	MN
Z	MP	MP	SP	Z	SN	MN	MN
SP	MP	SP	Z	SN	SN	MN	LN
MP	SP	Z	SN	MN	MN	MN	LN
LP	Z	SN	MN	MN	LN	LN	LN

Each of the 49 control rules represents the desired controller response to a particular situation. The block diagram presented in figure 9 shows a FLC controller in the Matlab simulation (ANFIS edit) and in figure 10 the simulation of the surface control is presented.

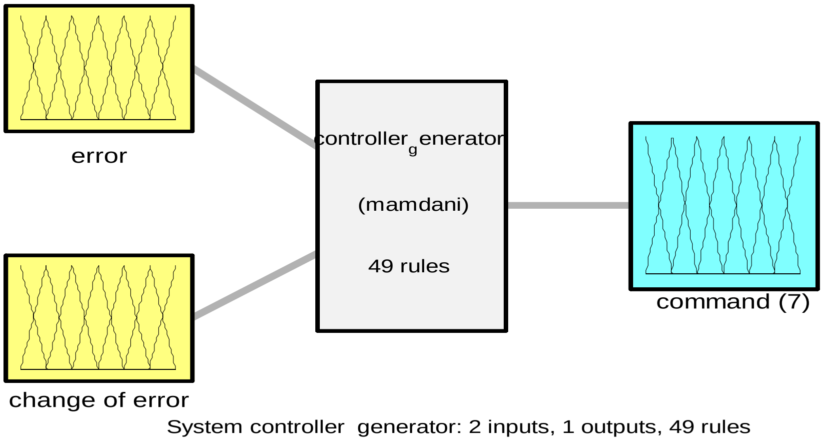


Fig.9 ANFIS using Matlab/Simulink software

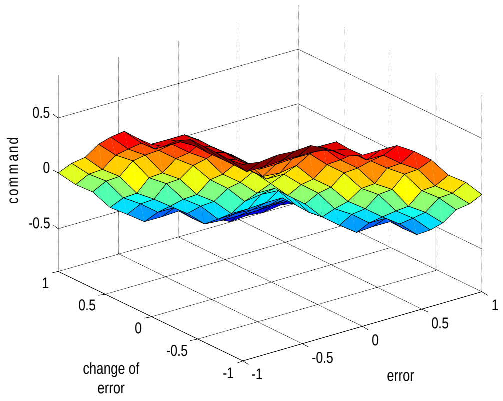


Fig. 10 The surface control

The block diagram shown in figure 11 shows a synchronous machine for which the output voltage is controlled by a PSS applied to its excitation system in the Matlab simulation .

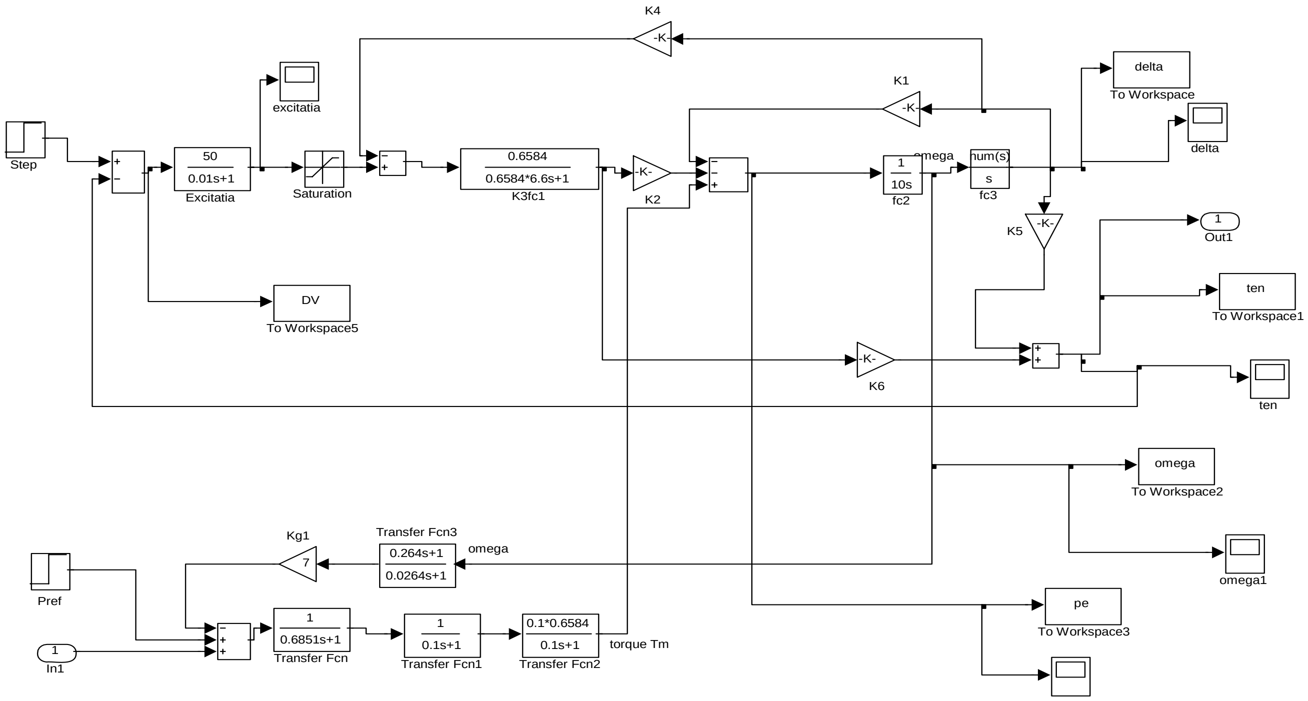


Fig. 11 Block diagram of one synchronous machine with PSS simulated in Matlab/Simulink software

Next figure shown the synchronous machine controlled by the fuzzy controller.

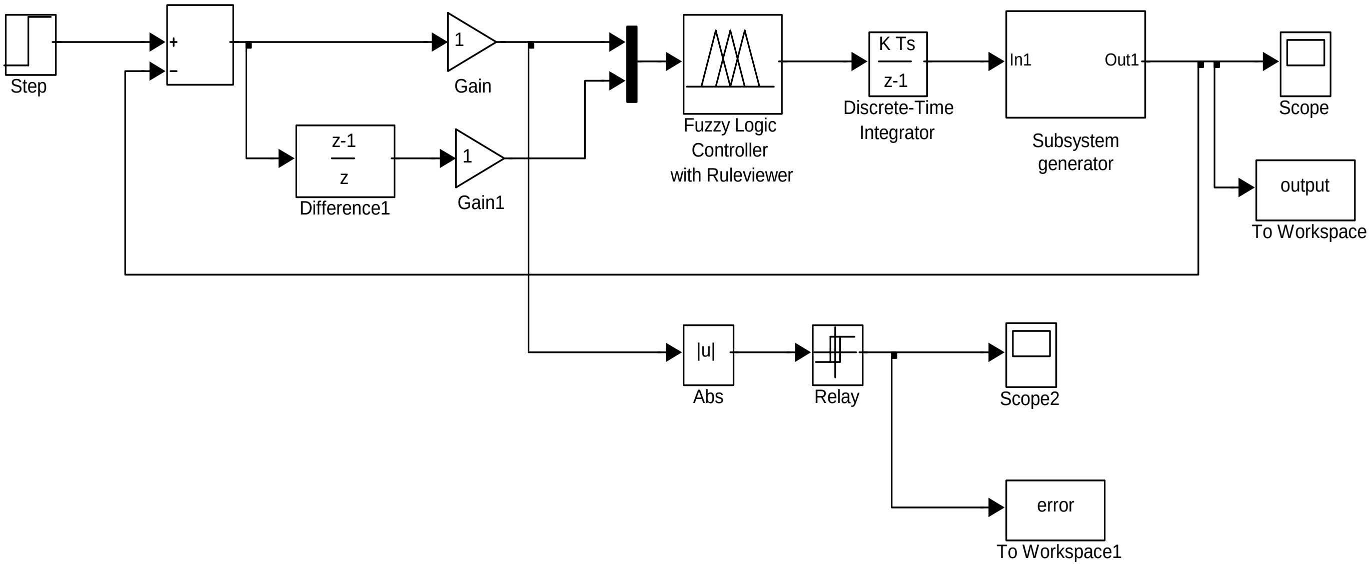


Fig. 11 Block diagram of synchronous machine with the fuzzy control simulated in Matlab/Simulink software.

In figure 12 is depicted the controlled output in both cases: step input response, with perturbations at time 10 s. At t=10s we can notice an increase of the mechanical torque (with 0.3 p.u.).

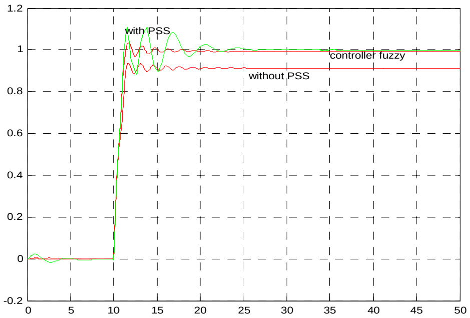


Fig. 12 Controlled outputs

VI. CONCLUSION

We could observe in both studies, from the Matlab/Simulink simulation, that the fuzzy controller has an excellent response with small oscillations, while the PSS response shows a ripple in both studies and some oscillations before reaching the steady state operating point. It was shown that an excellent performance of the fuzzy control in contrast to the conventional one for the excitation control of synchronous machines could be achieved.

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