

A Fuzzy Model Reference Learning Controller for Synchronous Generator Terminal Voltage Control

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Abstract

The control of synchronous generator terminal voltage and reactive power has been a disturbing problem to researchers and designers of power system engineers. This paper uses the fuzzy reference learning (FMRLC) scheme for automatic voltage regulation of synchronous generators and observes that it is superior to convectional AVR and adaptive self tuning controllers because it can tune the controller parameters and remembers what it tuned before. The simulation results obtained using FMRLC during abnormal operation of power system network shows reduction in settling time, percentage overshoot and steady state error

1. Introduction

The use of convectional automatic voltage Regulator (CAVR) in synchronous generators to control the terminal voltage and reactive power has been the common phenomena in power systems control. Synchronous generators are nonlinear systems which are continuously subjected to load variations and the CAVR design must cope with both normal load and fault condition of operation. Evidently, these conditions of operation result to considerable changes in the system dynamics. When the CAVR with fixed gain are used, the performance worsens and in some cases, introduces negative damping and degraded system stability [1]. So far, a lot of work has been done in synchronous machine excitation stabilization using AVR and controllers, all geared toward overcoming the problems enumerated above [2]. The short coming here is that the parameters of the controllers are fixed and so if the system dynamics changes as a result of faults, the controller will be tuned manually to adjust [3].

Modern control techniques are used extensively to achieve self-tuning (ST) control in synchronous generators. These include minimum variance (MV), generalized minimum variance (GMV), optimal predictor and pole placement (PP) [4,5,6]. In all these STAVR work, additional signals are used to improve robustness and are generally nonlinear. The MV generally gives very lively control and can be highly sensitive to non minimum phase plant. GMV, which is more robust and generalized, is vulnerable to unknown or varying plant dead time and can have difficulty with d.c offsets. PP aims to locate the closed-loop poles of the system at pre-specified locations leading to smooth controllers, but the algorithm shows numerical sensitivity when the plant model is over parameterized.

Of recent, a lot of research are going on in areas of application of soft computing (fuzzy and neural approach) in synchronous generator controls [7,8,9]. This work is based on fuzzy model reference learning controller. This belongs to the family of direct model reference adaptive controller.

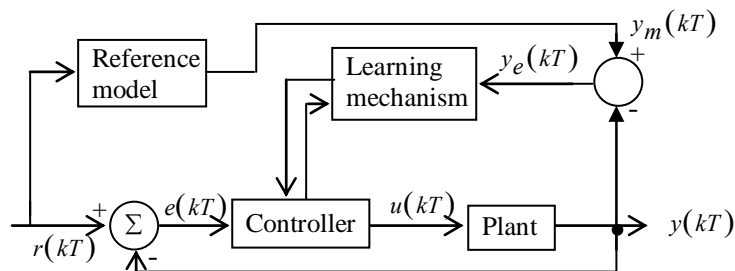
(FMRLC) in synchronous generator (SG) terminal voltage and reactive power control is designed so that its learning controller has the ability to improve the performance of the closed-loop

system by generating command inputs to the SG plant and utilizing feedback information from the SG. The FMRLC controller is superior to conventional self tuning controllers [5,10,11,12] which continues to tune the controller parameters because it will tune and to some extent remember the values that it had tuned in the past. Section 2 considers briefly the components of the FMRLC (Fuzzy controller, learning mechanism, reference model) while 3 models the synchronous generator (plant), section 4 is simulations.

2. The FMRLC Model

Figure 1 below shows the functional block diagram of the FMRLC. It is made up of four main parts; the plant, the fuzzy controller to be tuned, the reference model, and the learning mechanism (an adaptation mechanism). The FMRLC uses discrete time signals $r(kT)$, and $y(kT)$ with T as the sampling period. It also uses the learning mechanism to observe numerical data from a fuzzy control system. With this numerical data, it characterizes the fuzzy control system's current performance and automatically synthesizes or adjusts the fuzzy controller so that some given performance objectives are met. These performance objectives, which is the closed loop specifications are characterized through the reference model of figure 1.

Figure 1: Fuzzy model reference learning controller.



Here, the fuzzy control system loop operates to make $y(kT)$ track $r(kT)$ by manipulating $u(kT)$, while the adaptation control loop seeks to make the output of the plant $y(kT)$ track the output of the reference model $y_m(kT)$ by manipulating the fuzzy controller parameters.

2.1. The Fuzzy Cotroller

The synchronous generator which represents the plant has an input $u(kT)$ from the fuzzy controller and terminal voltage output $y(kT)$. The input to the fuzzy controller is the error $e(kT) = r(kT) - y(kT)$ and change in error $c(kT) = \frac{e(kT) - e(kT - T)}{T}$

where $r(kT)$ is a reference input.

A total of 121 fuzzy rules were employed as indicated below in table 1 with triangular membership functions.

Table 1: Decision table of 121 rules

Voltage Error e(kT)	Change in Voltage Error c(kT)										
	NV	NL	NB	NM	NS	ZR	PS	PM	PB	PL	PV
NV	NV	NV	NV	NV	NV	NV	NL	NB	NM	NS	ZR
NL	NV	NV	NV	NV	NV	NL	NB	NM	NS	ZR	PS
NB	NV	NV	NV	NV	NL	NB	NM	NS	ZR	PS	PM
NM	NV	NV	NV	NL	NB	NM	NS	ZR	PS	PM	PB
NS	NV	NV	NL	NB	NM	NS	ZR	PS	PM	PB	PL
ZR	NV	NL	NB	NM	NS	ZR	PS	PM	PB	PL	PV
PS	NL	NB	NM	NS	ZR	PS	PM	PB	PL	PV	PV
PM	NB	NM	NS	ZR	PS	PM	PB	PL	PV	PV	PV
PB	NM	NS	ZR	PS	PM	PB	PL	PV	PV	PV	PV
PL	NS	ZR	PS	PM	PB	PL	PV	PV	PV	PV	PV
PV	ZR	PS	PM	PB	PL	PV	PV	PV	PV	PV	PV

In the table above, NV, NL, NB, NM, NS, ZR, PS, PM, PB, PI, PV stands for negative very large, negative large, negative big, negative medium, negative small, zero, positive small, positive medium, positive big, positive large, and positive very large

Figure 2a: Membership functions for input universe of discourse.

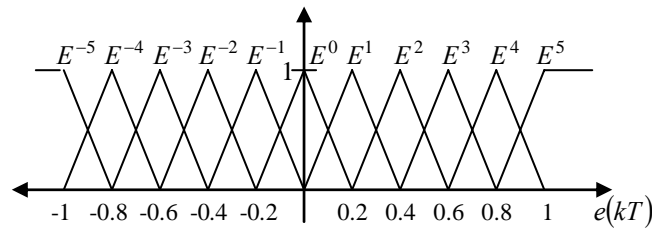
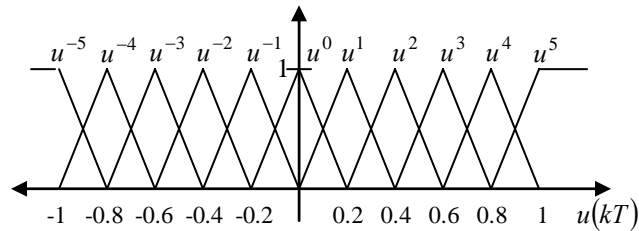


Figure 2b: Membership functions for output u



2.2. The Reference Model

A reference model

$$G(s) = \frac{1}{s+1} \tag{1}$$

is chosen because this model decays to zero in short time. If T = 0.1 sec, we can use bilinear transformation to find the discrete equivalent continuous time transfer function G(s) by replacing

$$s \text{ with } \frac{2}{T} \frac{z-1}{z+1} \tag{2}$$

Where

$$\frac{y_m(z)}{R(z)} = H(z) = \frac{1}{21} \frac{(z+1)}{z - \frac{19}{21}} \tag{3}$$

where $y_m(z)$ and $R(z)$ are the transforms of $y_m(kT)$ and $r(kT)$ respectively. So the discrete time implementation is

$$y_m(kT + T) = \frac{19}{21} y_m(kT) + \frac{1}{21} r(kT + T) + \frac{1}{21} r(kT) \tag{4}$$

2.3. The Learning Mechanism

The learning mechanism tunes the rule-base of the direct fuzzy controller so that the closed loop system behaves like the reference model. These rule-base modifications are made by observing data from the controlled process, the reference model, and the fuzzy controller. The learning mechanism consists of two parts: a fuzzy inverse model and a knowledge base modifier. The fuzzy inverse model (having the same rule base with the fuzzy controller) performs the function of mapping $y_e(kT)$ (representing the deviation from the desired behaviour) to changes in the process inputs $p(kT)$ that are necessary to force $y_e(kT)$ to zero. The knowledge-base modifier performs the function of modifying the fuzzy controller’s rule-base to affect the needed changes in the process inputs.

3. The Synchronous Generator Model (Plant)

Figure 3 below shows a functional block diagram of synchronous generator connected to busbar through a step-up transformer. It also indicates the terminal voltage/reactive power control loop using automatic voltage regulator (AVR) and the load frequency and real power control (LFC) loop using the governor. During faulted condition, a single machine infinite bus power system shown in figure 4 is used.

Figure 3: Power system network showing AVR and LFC loops

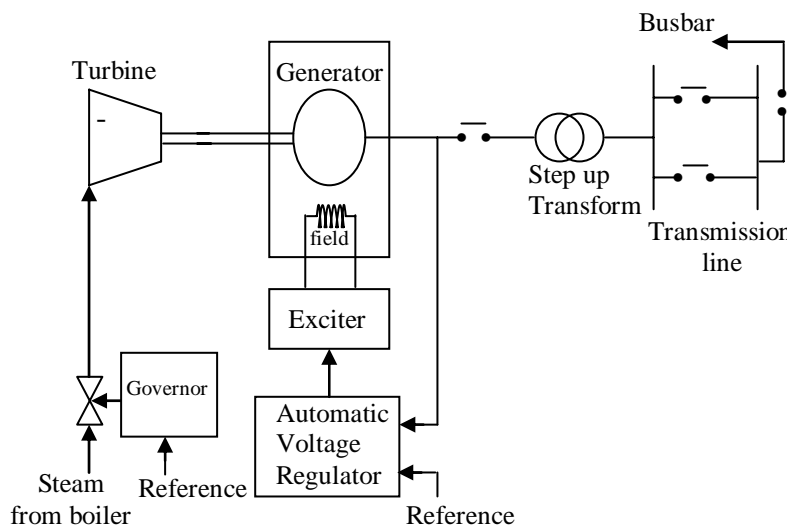


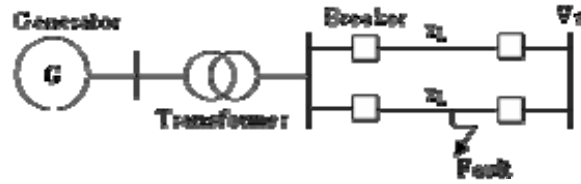
Figure 4: A single machine infinite bus power system

Figure 4 above is used to study the oscillation of the synchronous generator terminal voltage under faulted condition. It has been shown that the dynamic response of (SG) in a practical power system when a fault occurs is very complicated including many nonlinearities such as the magnetic saturation. However, the classical third order dynamic generator model has been commonly used for designing the excitation controller. This third order model [13,14] can be written as follows

Mechanical equations

$$\dot{\delta} = \omega \quad (5)$$

$$\dot{\omega} = -\frac{D}{2H}\omega + \frac{\omega_0}{2H}(P_m - P_e) \quad (6)$$

Generator Electrical dynamic

$$\dot{E}'_q = \frac{1}{T'_{do}}(E_f - E_q) \quad (7)$$

Electrical equations

$$E_q = \frac{x_{ds}}{x'_{ds}}E'_q - \frac{x_d - x'_d}{x'_{do}}V_s \cos \delta \quad (8)$$

$$P_e = \frac{V_s}{x_{ds}}E_q \sin \delta \quad (9)$$

$$I_q = \frac{V_s}{x_{ds}} \sin \delta = \frac{P_e}{x_{ds}I_f} \quad (10)$$

$$Q_e = \frac{V_s}{x_{ds}}E_q \cos \delta - \frac{V_s^2}{x_{ds}} \quad (11)$$

$$E_q = x_{ad}I_f \quad (12)$$

$$E_f = k_c U_f \quad (13)$$

$$V_t = \frac{1}{x_{ds}} \left[x_s^2 E_q^2 + V_s^2 x_d^2 + 2x_s x_d x_{ds} P_e \cot \delta \right]^{\frac{1}{2}} \quad (14)$$

$$x_{ds} = x_d + x_T + x_L, \quad x'_{ds} = x'_d + x_T + x_L$$

$$x_s = x_T + x_L$$

The definition of the parameters are given below

$\delta(t)$ power angle of the generator (in radian)

$\omega(t)$ relative speed (in rad/s)

P_m mechanical input power (in p.u)

P_e active power delivered to bus (in p.u)

E'_q transient EMF in the quadrature axis (in p.u)

V_t terminal voltage of the generator (in p.u)

By linearizing the above equations about the operating point, we have the state equation as

$$\dot{x} = Ax + Bu$$

$$y = cx \tag{15}$$

where state variables x is defined as

$$x = (\Delta\delta, \Delta\omega, \Delta E'_q) \tag{16}$$

and the control input and the output.

The matrices A, B, and C are given by

$$A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{-\omega_0}{2H} \frac{V_s}{x'_{ds}} E'_q \cos \delta & \frac{-D}{2H} & \frac{-\omega_0}{2H} \frac{V_s}{x'_{ds}} \sin \delta \\ \frac{-E'_q - x'_d I_d}{V_t} \left(\frac{-x'_d}{x'_{ds}} \right) V_s \sin \delta & 0 & \frac{-1}{T'_{do}} - \left(\frac{x_d - x'_d}{T'_{do}} \frac{1}{T'_{ds}} \right) \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ k_c/T'_{do} \end{bmatrix}$$

$$C = \begin{bmatrix} \frac{E'_q - x'_d I_d}{V_t} \left(\frac{-x'_d}{x'_{ds}} \right) V_s \sin \delta + \frac{x'_d{}^2 I_q}{V_t} \left(\frac{V_s}{x'_{ds}} \right) \cos \delta & 0 & \frac{E'_q - x'_d I_d}{V_t} \left(1 - \frac{x'_d}{x'_{ds}} \right) \end{bmatrix}$$

4. Simulations Results

Four test cases are simulated below,

4.1. A step input is applied to a normal CAVR with amplifier transfer function given by

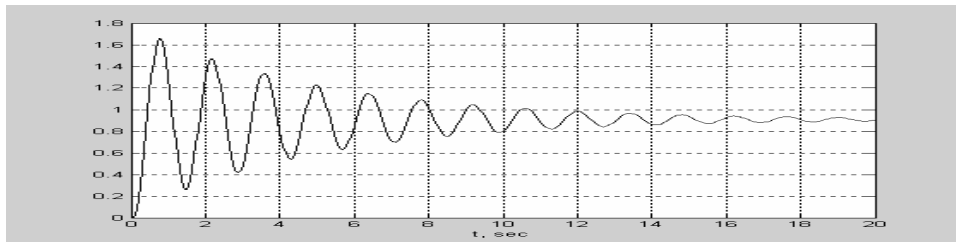
$$\frac{KA}{1 + \tau AS} \tag{17}$$

$$KA = 10, \tau G = 0.1, KE = 1, \tau E = 0.4$$

$$KG = 1, \tau G = 1, KR = 1, \tau R = 0.05$$

Below is the step response

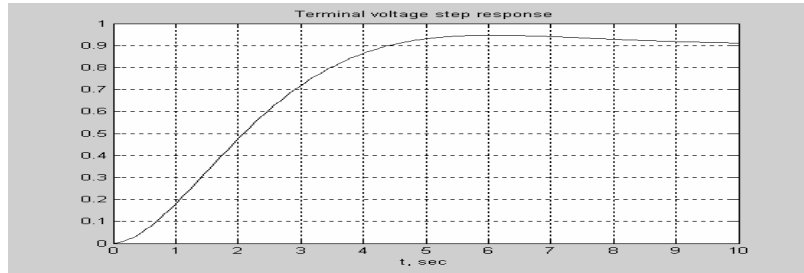
Figure 6: Terminal voltage step response for CAVR



4.2. A stabilizer is connected between the exciter output and the input summer with a step input signal. The parameters above remained the same but the stabilizer has transfer function given by

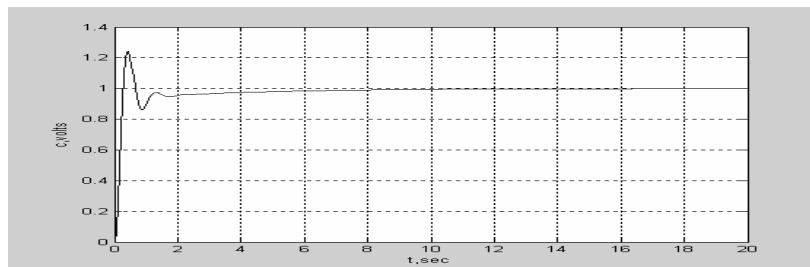
$$\frac{2s}{0.04s + 1} \tag{18}$$

Figure 7: Terminal voltage step response of CAVR with stabilizer



4.3. A PID is connected in series with the amplifier and a step input applied. The PID has $k_P = 1.0$, $k_I = 0.25$ and $k_D = 0.28$.

Figure 8: Terminal voltage step response with PID controller



4.4. FPI-AVR is used in place of PID. The response for a step input is shown in figure 9 (a) and (b). A three phase fault is applied to the line and cleared after two seconds. Fig10 (a) and (b) shows the response

Figure 9: Step response of FPI-AVR

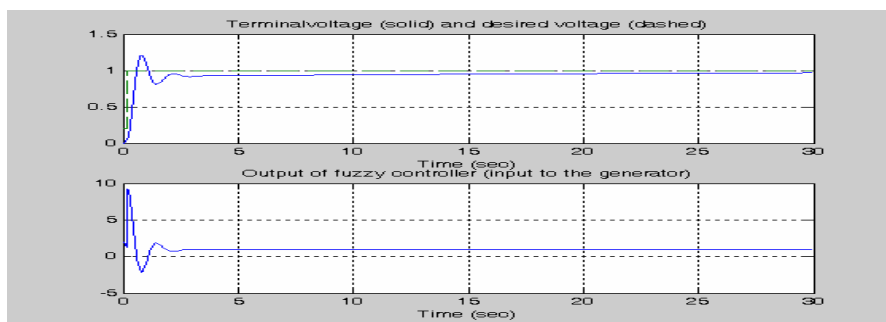
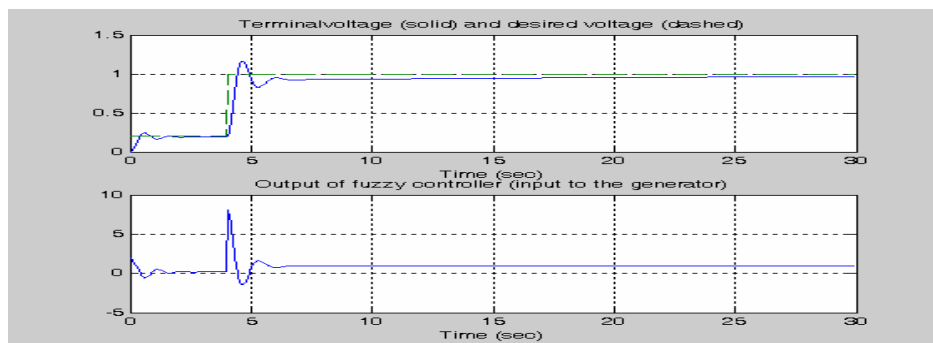
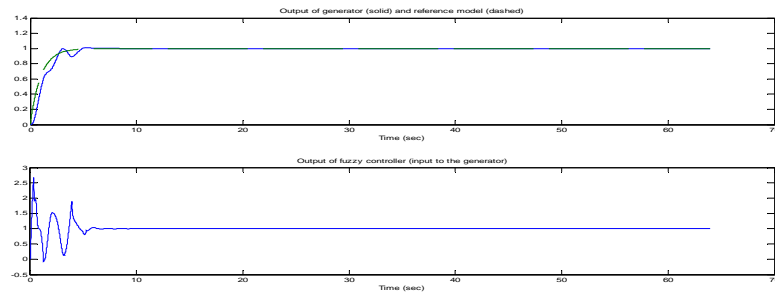


Figure 10: Step response of FPI-AVR to a three phase fault.



4.5. An FMRLC is used in place of the PID and a step input applied as shown in fig.5.

Figure 11: Terminal voltage step response with FMRLC controller



5. Conclusion

This paper reviewed the various techniques employed in synchronous generator terminal voltage control. Such techniques are the CAVR, MV, GMV, PP and ordinary fuzzy controller. It identified some of the limitation of each of them, such as the steady state error presented by ordinary fuzzy controller. The application of fuzzy model reference learning controller is the main focus of this paper. Not only that this controller is adaptive in nature but the behavior of the plant is controlled by identifying (11×11) rules which took care of most nonlinear operating conditions which wouldn't have been a problem by convectional adaptive and non-adaptive controllers.

The simulation results for disturbed terminal voltage values and transmission lines faults shows a very sharp reduction in settling time, over shoot, rise time and zero steady state error.

The implementations are achieved using microcontroller, A/D and D/A converters.

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