EXCITATION CONTROL OF SYNCHRONOUS GENERATORS USING FUZZY TECHNIQUE

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ABSTRACT

A synchronous generator excitation system is presented in this paper with a fuzzy logic controller having a nonlinear input output relationship. The excitation control is performed with either Mamdani or Sugeno model. The aspects and performances are reported in this paper. The digital implementation of the proposed controller is done using a PC equipped with a data acquisition system. A PWM pulse stream of desired width and frequency is generated and communicated to a MOSFET based chopper. The fuzzy controller makes the necessary adjustments and corrections in the PWM pattern needed for regulating the generator excitation. The performance is found quite satisfactory. Design methodology and experimental results are presented in this paper.

INTRODUCTION

The aim of alternator excitation control is to keep its output voltage constant under various conditions of disturbances. The supply for the excitation is normally obtained from the mains through controlled rectification and filtering. The excitation current should be free from ripples to generate a smooth sinusoidal voltage in the generator armature. Controlled rectifiers have low power factor and are discarded in modern applications. The chopper-based controller at high switching frequency can operate at unity power factor. For this reason chopper based exciters are gaining popularity over controlled rectifiers. Conventionally, PWM pattern is chosen by a linear, weighted or step process [1]. These processes fail to address the highly nonlinear relationship between excitation and the alternator output voltage. But the fuzzy controller is equally suited to nonlinear as well as linear systems [2]. Moreover as the conventional process does not encourage multiple inputs, they usually neglect the past results, which can be easily accommodated in fuzzy controllers, as fuzzy is multiple input multiple output system by nature [2]-[5]. Another advantage of using fuzzy controller is that it does not require any mathematical modeling of the alternator, whereas conventional process requires it and thus is not suitable for general design specification. The underlying principal used here is to change the effective voltage of the excitation control winding by using a chopper. The PWM pattern fed to the chopper in turns defines the output voltage. A series of different pattern is stored in the EPROM, preprogrammed for the desired result. Selection of the required PWM pattern is done using the fuzzy logic controller.

EXCITATION CONTROL

The excitation control of a synchronous generator is needed for stabilizing its RMS terminal voltage. The RMS output voltage of a generator is proportional to the field excitation and may be represented as

$$V_{RMS} = f\left(N_S Z f\right) \qquad (1)$$

Where, N_s is the speed of the prime mover, Z is the number of winding turns in each phase and ϕ is the flux per pole. The flux ϕ is dependent on the field current I_f. The relation between the flux ϕ and the field current I_f is not linear all over the operating range. The field current is a direct function of the DC voltage (V_{out}) applied across the field winding. Thus the generator output voltage may be represented as

$$V_{RMS} = f\left(N_S Z V_{out}\right) \qquad (2)$$

For an ac generator, the supply frequency is kept constant by keeping the prime mover speed constant by using a governor. From (2) it is evident that the terminal voltage depends upon the field dc supply (V_{out}). A chopper is suitable for efficient control of field excitation. The duty cycle of a chopper may be adjusted to give variable dc voltage output. A typical PWM pattern for a chopper is shown in Fig. 1.

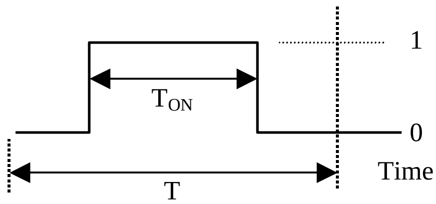

Fig. 1 PWM pulse pattern for the chopper circuit.

The state '0' means the chopper is OFF and state '1' means that the chopper is ON. The average dc voltage output of the chopper is governed by

$$V_{out} = V_{dc} \frac{T_{on}}{T} = DV_{dc} \qquad (3)$$

Where, T_{on} is the duration of the pulse within a period T, V_{dc} is the chopper input voltage, V_{out} is the dc voltage output and D is the duty cycle ($D = T_{on}/T$). In case of any disturbance, the terminal voltage (RMS value) of a synchronous generator would not be constant.

To keep the RMS terminal voltage to a constant value, the dc supply to the field circuit should be changed. This change is accomplished by adjusting the T_{on} time. Considering an adjustment of dT_{on}, the resultant output dc voltage of the chopper would be

$$V_{out} = V_{dc} \frac{T_{on} + dT_{on}}{T} = D' V_{dc} \qquad (4)$$

THE FUZZY CONTROLLER

In fuzzy logic, calculations are done using some rules and membership functions. The processing stage invokes each appropriate rule and generates a result for each, then combines the results of the rules; and finally the output stage converts the combined result back into a specific control output value. The crisp input value is manipulated in four different steps. All the processes involved are described below, with reference to the experimental parameters used. The difference between the desired voltage (RMS) and the actual terminal voltage of the generator is designated as V_{err}. The difference between the present output (RMS) voltage and the previous output is designated as dV.

Fuzzification

Crisp input values are given to the input membership functions defined for each input and corresponding weighted values are obtained to the degree of their truth-value. Present error voltage (V_{err}) and rate of change of the output voltage (dV) are used as inputs. Three triangular shaped membership functions for each input are chosen. Range used for the error voltage (V_{err}) is from -90 to +90. Membership functions are named negative far (NF), close (C) and positive far (PF). Similarly, rate of change of voltage (dV) is the same having names negative change (NC), stable (S) and positive change (PC). The input MFs for V_{err} and dV are shown in Fig. 2.

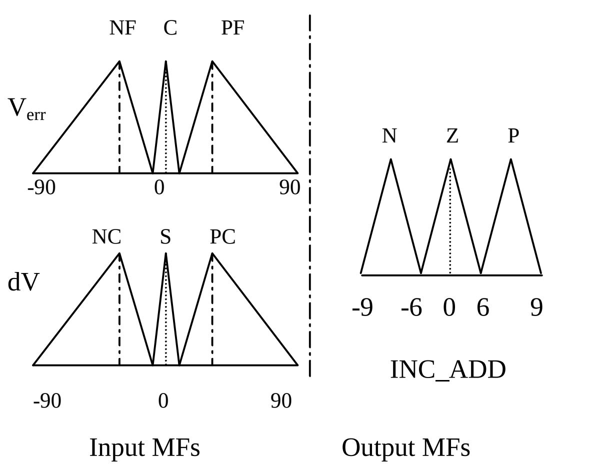

Fig. 2 Input membership function for V_{err} and dV for Mamdani Model.

Same input membership functions are used for implementing the Sugeno model as well. The parameters of all the membership functions are shown in Table I. The output membership functions for Mamdani and Sugeno models are different and are shown in Table II. This output value of Fuzzy Controller is composed of three triangular shaped membership functions: negative (N), zero (Z) and positive (P) having a span of –9 to 9.

Inference

The truth-value for the premise of each rule is computed using the crisp input values of V_{err} and dV, and applied to the conclusion part of each rule. Three rules are used for composition of output subset from the weighted input values and are same for both Mamdani and Sugeno models. The rules are extracted from the behavior of the system. An example of the disturbance is shown in Fig. 3.

Table I Input membership function parameters for Mamdani and Sugeno models.

Error voltage (V_{err})				Output voltage change (dV)			
	Start	Peak	End		Start	Peak	End
NF	-90V	-10V	-0.5V	NC	-90V	-10V	-0.5V
C	-0.5V	0V	0.5V	S	-0.5V	0V	0.5V
PF	0.5V	10V	90V	PC	0.5V	10V	90V

Table II Output membership function parameters for the Mamdani and Sugeno models.

INC_ADD	Mamdani model			Sugeno model
	Start	Peak	End	Spike position
N (Negative)	-9	-6	-3	-6
Z (Zero)	-3	0	3	0
P (Positive)	3	6	9	6

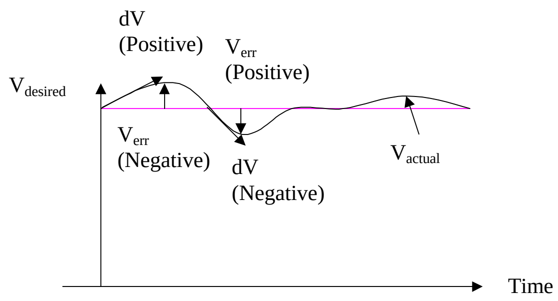

Fig. 3 Example of disturbance for extracting the fuzzy rules.

It is observed from Fig. 3 that if the error voltage (V_{err}) is negative and the derivative of the output voltage (dV) is positive then the dc excitation should be reduced. On the other hand if the error voltage (V_{err}) is positive and the derivative of the output voltage (dV) is negative, then the dc excitation should be increased to keep the output voltage equal to the desired one. Using these philosophies, the following rules are framed for the fuzzy controller:

1. If (Verr is C) or (dV is S) then (INC_ADD is Z)
2. If (Verr is PF) or (dV is NC) then (INC_ADD is P)
3. If (Verr is NF) or (dV is PC) then (INC_ADD is N)

Composition

All of the fuzzy subsets assigned to each output variable are combined together to form a single fuzzy subset for each output variable. Three triangular shaped output membership functions are assigned here that are negative (N), zero (Z) and positive (P).

Defuzzification

This is the process of converting the fuzzy output subset to a crisp number suitable for practical use. The difference between Mamdani and Sugeno method lies principally on the defuzzificaion process. For Mamdani method, the output crisp value is taken as the centroid of the output subset obtained, whereas weighted average is used in Sugeno method. The output crisp value gives directly the incremental change in the PWM pattern needed for the stabilization process. A lookup table based implementation procedure is adopted for the controller. Pre-calculated PWM patterns of different duty cycles are stored in ascending order in an EPROM. The address of a PWM pattern is related to its duty by

$$EPROM_{address} = \left(\frac{D - D_{\min}}{D_{\max} - D_{\min}} \right) (N - 1) \qquad (5)$$

where, D_{min} is the minimum duty cycle, D_{max} is the maximum duty cycle and N is the number of stored patterns. The fuzzy controller output (INC_ADD) is used to update the new address of the PWM pattern.

$$\left(EPROM_{address} \right)_{new} = \left(EPROM_{address} \right)_{old} + \text{INC\_ADD} \qquad (6)$$

A typical defuzzification process is illustrated in Fig. 4. For V_{err} = 10.7V and dV = 3.07V, the defuzzified outputs for the Mamdani and Sugeno models are 2.18 and 3.43 respectively. Since the address should have integer values, INC_ADD is rounded. The computation of the output from the fuzzy controller depends upon the model used for the implementation. Brief descriptions of the computation process are summarized for both the models.

Mamdani Model

The shapes of the output membership functions become trapezoidal shaped as its top is truncated for computing its contribution to the desired output. A trapezoid can be considered as combinations of two triangles and one rectangle. The output of the three membership functions can be divided into six triangles and three rectangles. Thus for computing the centroid of the crisp output, nine segments are needed at a time for any kind of input combinations. In the proposed controller, the centroid (INC_ADD) is calculated using

$$\text{INC\_ADD} = \sum_{j=1}^{9} x_j A_j \Bigg/ \sum_{j=1}^{9} A_j \qquad (7)$$

Where x_j is the distance of the centroid of the segment 'j' having area A_j.

Sugeno Model

The three weighted output spikes are used to calculate the weighted average (INC_ADD) using

$$\text{INC\_ADD} = \sum_{j=1}^{3} a_j x_j \Bigg/ \sum_{j=1}^{3} a_j \qquad (8)$$

Where x_j are positions in x-axis and a_j are magnitudes of the corresponding spikes. The output of the fuzzy controller with the Mamdani model at different inputs is shown in Fig. 5. The controller sensitivity is constant (at a high value) in case of large disturbances. As the error comes closer to zero, the response is comparatively faster.

IMPLEMENTATION TECHNIQUE

An opto-coupler isolated chopper, driven by the PWM pulse stream, is used to control the terminal voltage by varying the excitation level, as shown in Fig. 6. A potential transformer (PT) is connected to the terminal of the synchronous generator. The PT output voltage is then rectified, filtered and fed to the analog port of the data acquisition card.

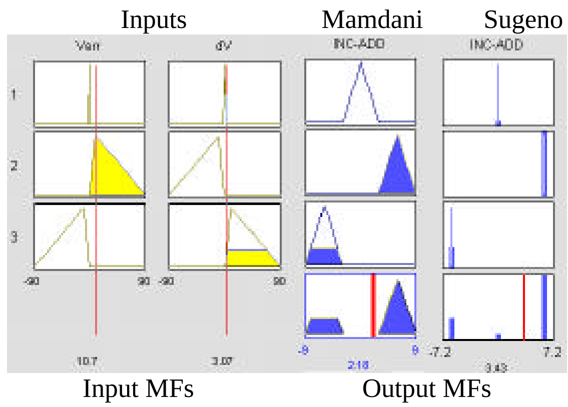

Fig. 4 Typical input output relationship in the Fuzzy controller (Mamdani and Sugeno).

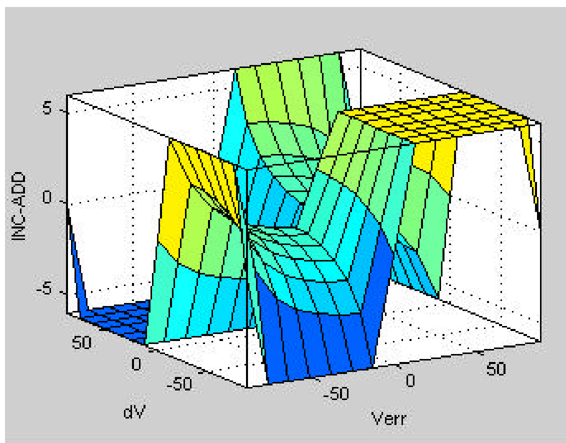

Fig. 5 The output surface obtained using fuzzy toolbox of MATLAB (Mamdani).

The implementation is done with a PC. The PC is used for selecting the appropriate duty cycle (D) needed for stabilizing the output voltage. The detail scheme is shown in Fig. 6. The feedback voltage from the alternator terminal is fed to the PC through a data acquisition system card (DAS PCLS-812PG). The DAS card has a 12-bit A/D converter and can be set to a conversion rate of 30kHz. PWM patterns of different duties are stored in the EPROM. In the proposed scheme NM27C512 EPROM is used. It has 16-bit address and 8-bit data bus. The upper 6 bits (AD_{10}-AD_{15}) of the address bus are used for the PWM pattern selection and the lower 10 bits (AD_0-AD_9) are used for generating the real time PWM waveform. There are 1024 samples in a PWM pattern and hence the resolution is high.

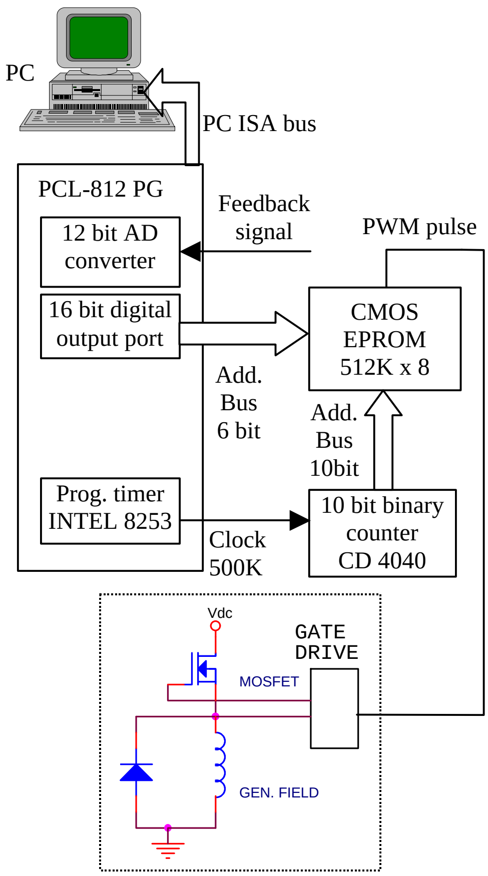

Fig. 6 Fuzzy excitation controller scheme.

With this setup upto 64 different patterns (duty cycles) can be accessed. The setting of minimum and maximum duty cycle of the chopper depends upon the input and output voltage ratio and also on the limit of disturbance. In the experimental setup the minimum and maximum duties are set to 5% and 95% respectively. The PWM pattern at the starting address of the EPROM, $(0000000000000000)_b$ to $(0000011111111111)_b$ are set to zero. During reset state, the EPROM is assigned this starting address ensuring OFF state of the chopper in idle condition. The real time waveform is generated at the D_0 line of the data bus. The analog feedback voltage is acquired through the DAS A/D converter, which is weighted and deducted from the desired voltage. This gives an error voltage (V_{err}), which is then supplied to the fuzzification process along with the instantaneous deviation of terminal voltage. Two popular fuzzy models, Mamdani and Sugeno are used. After defuzzification, INC_ADD is obtained for the error correction.

Software Program

A real time program is written to implement the fuzzy rules and to accomplish fuzzification and defuzzyfication process. The program also operates the Lab-card for selecting the appropriate PWM pattern. A flow chart for the program is shown in Fig. 7. The program starts with initializing the DAS card and the timer clock frequency. A desired value of output voltage of the generator is set within the program that can be changed on-line during the program execution using the keyboard. The digital value of the analog sample voltage of generator output from the AD converter is then acquired and is calibrated to obtain the error voltage.

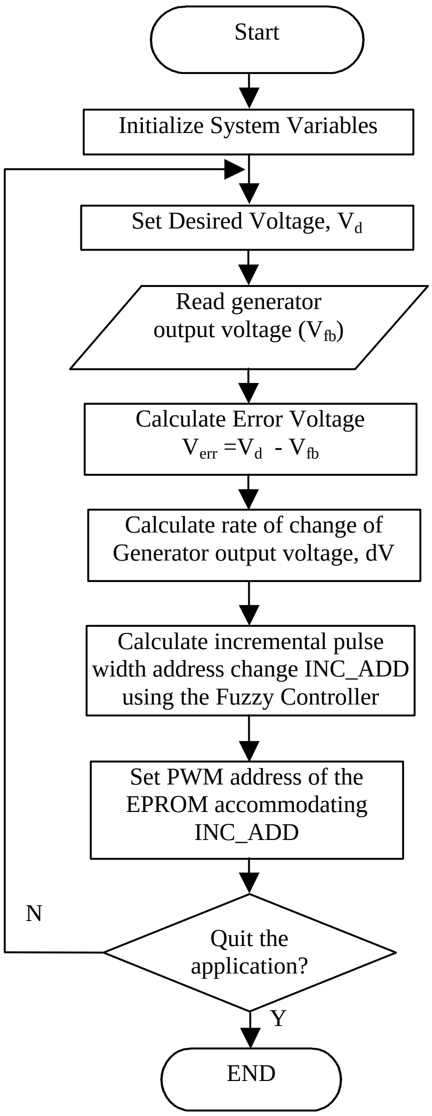

Fig. 7 Program flowchart of the fuzzy controller.

This calculated error voltage and rate of change of output voltage are used as the crisp input value for the fuzzy processor. The program has options to select either the Mamdani model or the Sugeno model. If any modification of the PWM pulse is required, it is done by changing the address value of the EPROM accessed by the digital output port of the DAS card. Then the program searches for any user request. If a quit request is got from the keyboard, the program stops all the running processes and resets the PWM data to 0% duty (starting PWM address of the EPROM). Otherwise the program repeats the normal loop.

EXPERIMENTAL RESULTS

The proposed fuzzy based generator excitation control is built in the laboratory and tested on a prototype chopper. One counter of 8253 of the DAS card is set to square wave clock generator mode at a frequency of 500KHz. The chopper is driven from a 60V dc supply. The start up, steady state and dynamic state responses of the controller are studied for both Mamdani and Sugeno models. The reference voltage is set to 30V (RMS). The response of the fuzzy controller with Mamdani and Sugeno models are shown in Figs. 8 and 9 respectively. The magnitude error in Sugeno model is more compared to the Mamdani model. The startup and dynamic responses are comparable. Both models have some overshoots in the transient periods. However this is natural in all types of controllers.

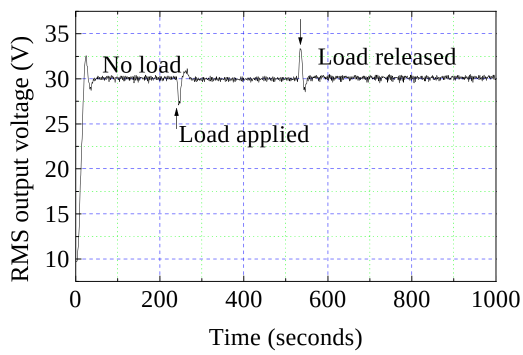

Fig. 8 Generator terminal voltage (RMS) output at different operating conditions (Mamdani model).

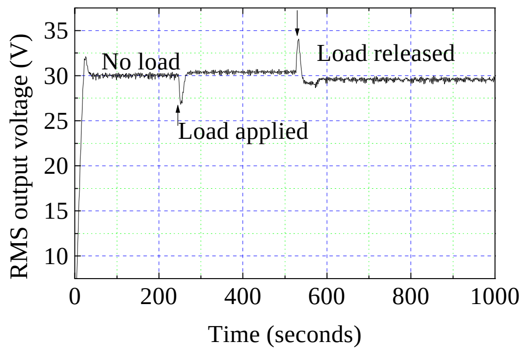

Fig. 9 Generator terminal voltage (RMS) output at different operating conditions (Sugeno model).

CONCLUSIONS

A fuzzy logic based excitation controller of a synchronous generator is proposed in this paper. The aim is to keep the terminal voltage of the synchronous motor constant to a predefined magnitude. Two different fuzzy models are applied for realization of the controller. The performance of the controller is studied for both models independently. The controller is tested on a PC based experimental setup with three membership functions. The steady state and dynamic response of the controller is found quite satisfactory with the Mamdani model of realization. The Sugeno model based realization of the fuzzy controller has some magnitude error. There are scopes of further improvement by increasing the number of membership functions. Because of adaptation of simplified procedures, the computation time of the fuzzy controller is moderate. This makes the fuzzy controller economically feasible for practical applications.

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