A FUZZY LOGIC-BASED SYNCHRONOUS GENERATOR VOLTAGE REGULATOR OPTIMIZED WITH A GENETIC ALGORITHM

B.J. LaMeres[1] and M.H. Nehrir
Electrical & Computer Engineering Department
Montana State University
Bozeman, MT 59717

ABSTRACT: This paper describes the design and optimization of a fuzzy logic-based voltage regulator for a synchronous generator optimized with a genetic algorithm. The proposed design will regulate the armature voltage of an alternator under varying loads by controlling the excitation current into the field of the machine. Once the design is complete, the time response of the fuzzy logic controller will be optimized using a genetic algorithm. The optimization will reduce the reaction time of the controller while limiting oscillations. The design of the fuzzy logic controller and the steps taken by the genetic algorithm to optimize the system are presented. Simulation results are given to support the proposed design procedure.

KEYWORDS: synchronous generator, voltage regulation, fuzzy logic, genetic algorithm

I. INTRODUCTION

Fuzzy logic controllers are rapidly becoming a viable alternative to classical controllers [1,2]. The reason for this is that a fuzzy controller (FLC) can closely imitate human control processes. Fuzzy logic technology enables the use of engineering experience and experimental results in designing an embedded system. In many applications, this circumvents the use of rigorous mathematical modeling to derive a control solution.

One of the main advantages of using a fuzzy logic control strategy is that it allows a model-free estimation of the system. In other words, the designer does not need to state how the outputs depend mathematically upon the inputs. A fuzzy controller can be developed by encoding the structured knowledge of the system.

While the advantage of using a model-free estimation of the system is very appealing, it leads to some problems when trying to optimize the controller. Without knowing the detailed mathematics of the system, classical control methods cannot be used to increase time response and to damp oscillations. This problem can be handled using a trial and error method. But this approach lacks scientific credibility and will usually not yield an optimal solution.

Genetic algorithms are optimization techniques based on natural population genetics [6] which are suited well for the optimization of a FLC. This is because a genetic algorithm treats the system as a black box and is only concerned with the quality of the output of the controller.

---

[1] Presently with Hewlett Packard Co., Colorado Springs, CO.

In this paper the design of a fuzzy logic-based voltage regulator for a synchronous generator, which is optimized by a genetic algorithm, is presented. The controller uses the armature voltage error and its rate of change as the input variables to the FLC. The output signal from the FLC is multiplied by a gain multiplier (K), which is fed into a proportional-integral-derivative (PID) controller for signal stabilization. The output of the PID controller is a voltage signal, fed to the field winding of the generator, which will control its field current in order to keep its terminal voltage at a desired level under an electrical disturbance. Fig. 1 shows the block diagram of the proposed controller. A genetic algorithm is used to optimize K so that the armature voltage returns to its desired value in minimum time and with minimum possible overshoot.

The rest of this paper presents the design of the fuzzy logic voltage regulator, the genetic algorithm optimization technique used, simulation results to support the proposed design procedure, and conclusions.

II. THE FUZZY LOGIC CONTROLLER

Fuzzy logic control is a non-mathematical decision algorithm that is based on an operator's experience. This type of control strategy is suited well for non-linear systems such as the synchronous generator, which exhibits non-linearity between the field current in and the armature voltage out [3-5]. The controller in this design is a *proportional differential integrator* (PID). This type of control strategy is ideal for the excitation control of a synchronous generator because the control signal is allowed to ramp up or down depending on the type of load that is present.

The fuzzy logic controller is developed using the immediate value of the armature voltage. The output signal is then scaled down in incremental steps and is fed into the PID controller for signal stabilization. This step can be either positive or negative. As the system runs, the steps will be continually summed up to provide the output signal to the field of the generator. When a series of positive steps are output from the fuzzy logic controller, the PID output will begin to *ramp-up*, and conversely, if a series of negative steps are output from the fuzzy logic controller, the PID output will begin to *ramp-down*. When the generator armature voltage is at its desired value, the PID output step will take on a value of zero. The amount that the output of the FLC is stepped down or up is determined by a constant multiplying factor (K). This constant will determine how large or small the incremental steps are that are integrated by the PID controller. The larger the incremental steps, the faster response the system will have. It is desired to have the fastest system possible without oscillations. The oscillations in this system result from the time delay between the input into the field of the generator and the output voltage at the armature terminals, which is due to the inductive nature of the alternator. It is difficult to determine the proper value of K in this fuzzy-controlled system because it uses a model-free estimation. A genetic algorithm (GA) will be used to optimize the time response of the system after the controller is designed.

The first input to the fuzzy controller is the voltage error (Vref – V) between the desired value of the generator armature voltage and its immediate value. The error signal will determine whether the field current needs to be increased or decreased in order to bring the voltage back to its desired value. The second input into the controller is the rate of change of voltage error, which will determine how fast the output voltage is changing. This is an important factor in a real-time control strategy for increasing the time response of the system.

The output of the fuzzy logic controller corresponds to the amount the generator field current should be increased or decreased in order to bring the output voltage to its desired value. The linguistic variables used (in the fuzzification process) for the *voltage error (e)* and the *rate of change of error (del e)* are labeled as zero (ZE), positive small (PS), negative small (NS), etc. Fig. 2 shows the membership functions used to fuzzify the inputs and output variables. The rule matrix relating the linguistic input variables to the output variable is given in Table 1. The rules are derived based on human experience [4,5]. A typical rule obtained from the rule matrix is: If the "voltage" is negative large (NL), AND the "rate of change of voltage error" is negative large (NL), then the "field current" is positive large (PL). The linguistic output signal is converted to a crisp value using the centroid deffuzification method [2].

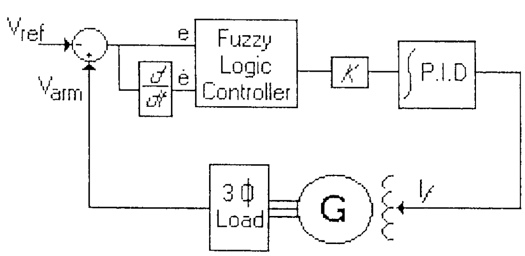

Fig. 1 Closed Loop Control System.

Table 1. Fuzzy logic rule matrix.

		Voltage Error						
		NL	**NM**	**NS**	**ZE**	**PS**	**PM**	**PL**
	NL	PL	PL	PL	PL	PM	PS	ZE
	NM	PL	PL	PM	PM	PS	ZE	NS
Del	**NS**	PL	PM	PS	PS	NS	NM	NL
Volt	**ZE**	PL	PM	PS	ZE	NS	NM	NL
	PS	PL	PM	PS	NS	NS	NM	NL
	PM	PM	ZE	NS	NM	NM	NL	NL
	PL	ZE	NS	NM	NL	NL	NL	NL

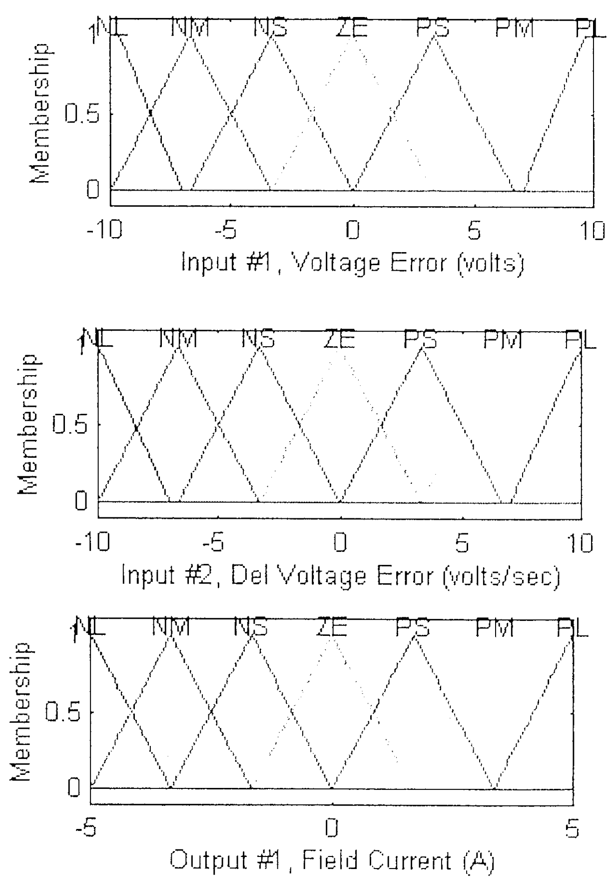

Fig. 2. Membership functions of the fuzzy logic controller.

III. CONTROLLER OPTIMIZATION USING A GENETIC ALGORITHM

A. A Brief Overview of Genetic Algorithms: In this subsection, a brief overview of genetic algorithms is given. Detailed information on this subject is readily available in subject-related textbooks, i.e. [6].

Genetic algorithms are stochastic optimization algorithms which have proved to be effective in various applications. A given GA emulates the process of evolution and natural selection, which is based on an idea that the force driving species to evolve can be imitated in an artificial context. A typical GA maintains a population of solutions and implements a "survival of the fittest" strategy in the search for better solutions. It has been shown to be capable of finding global optimization points in complex problems by exploring virtually all regions of the state space and exploiting promising areas by generating new and improved population from the old ones through the commonly used operations, i.e. selection, crossover (reproduction) and mutation, applied to individuals in the populations [6].

B. Controller Optimization: To develop an optimal fuzzy logic voltage regulator, two conditions must be met. The first condition is that the terminal voltage of the generator returns to its desired value as quickly as possible upon loading. The second condition is that there is little or no overshoot resulting in oscillation. These two variables are shown in a generator voltage response given in Fig. 3.

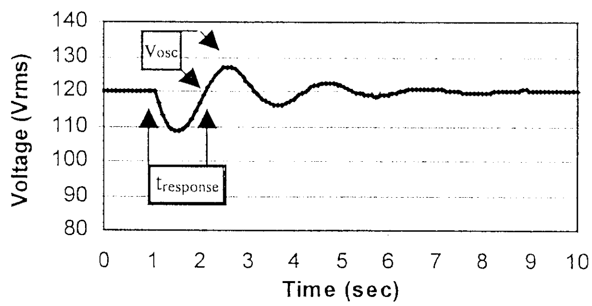

Fig. 3. Variables for an optimal fuzzy controller.

These two variables ($t_{response}$, and overshoot (v_{osc})) must be minimized in order to obtain an optimized and stable voltage regulator. The following equation shows the basic function that will be optimized using GA.

$$f(t_{response}, v_{osc}) = [\frac{1}{t_{response}} + \frac{1}{v_{osc}+1}]$$

There is a unity term in the denominator of the above expression because ideally the overshoot will be minimized to zero. The two variables are linked in a highly non-linear fashion and ideal for optimization using GA.

The variable that will be changed (in order to optimize the above function) is the multiplying constant K shown in Fig. 1. By increasing K, the incremental steps to be summed by the PID block will be larger and the generator will respond faster. However, if the system becomes too fast, oscillations will occur. The GA in this design reduces the time response while limiting oscillations.

IV. SIMULATION RESULTS

Simulation studies were performed to investigate the performance of the proposed fuzzy logic-based automatic voltage regulator for the synchronous generator optimized with a genetic algorithm. A resistive load was applied across the generator resulting in its terminal voltage to drop below its rated value of 120 V. However, the FLC controlled the generator field excitation to bring the terminal voltage to the desired level.

Fig. 4 shows the generator terminal voltage response after a sudden application of a resistive load. For comparison purposes, three responses are shown: 1) with the PID controller acting alone, K = 0.01; 2) with both FLC and PID controllers acting without GA optimization (FPID), K = 0.01; and 3) with the FPID controller acting with GA optimization (FPID-GA), in which case the value of gain is found to be K = 0.023. It is clear from this figure that the generator voltage is returned to its desired level faster and with less undershoot when the FPID – GA optimized controller is used. Fig. 5 shows the generator voltage response after a sudden application of a capacitive load with the FPID-GA optimized controller in place. In this case the generator voltage tends to increase, but it is returned to its desired (reference) value with the aid of the controller.

It was noticed that when the gain of the fuzzy controller was set to a value greater than its optimized value, the generator voltage response became oscillatory. Fig. 3 shows the generator voltage response to a sudden application of a resistive load with the gain of the FPID controller set to K = 0.04, which is greater than its GA-optimized value of K = 0.023.

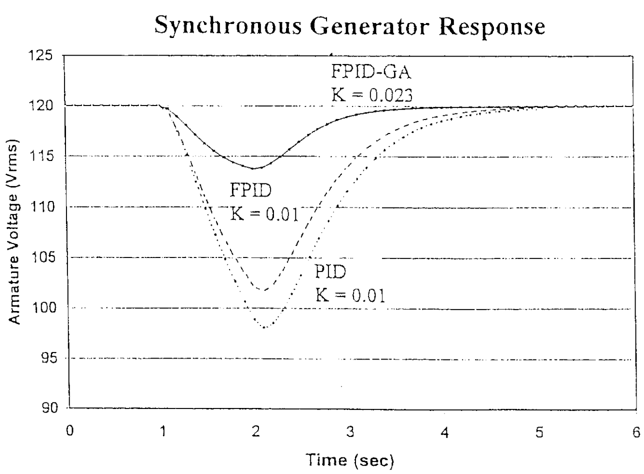

Fig. 4. Comparison of generator voltage responses to a sudden resistive loading.

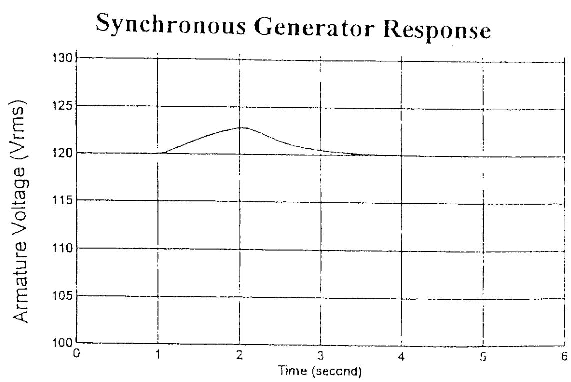

Fig. 5. Generator voltage response (capacitive loading) using the FPID-GA controller.

V. CONCLUSION

This paper presented an optimized fuzzy logic controller for automated voltage regulation of a synchronous generator. It was shown that a model free estimation of the system was sufficient to develop a functional fuzzy controller, but the model free estimation was insufficient to scientifically reduce the time response. The application of a genetic algorithm was presented as a way to solve this problem. By including a parameter that would increase or decrease the incremental steps to the PID portion of the system, the response could be controlled. A genetic algorithm was used to optimize this parameter in order to achieve the lowest response time while limiting oscillations. Simulation results were presented to illustrate the impact of the GA-optimized controller gain in shortening the response time while limiting oscillations.

The methodology presented in this paper works well for off-line optimization. However, a data bank of optimized gain values, which includes gains for different operating conditions needs to be added to the controller to make it useful for on-line applications.

ACKNOWLEDGEMENT

This work was supported by the National Science Foundation under Grant ECS-9616631. Mr. Jie Lu's valuable suggestions during the course of this project are acknowledged.

REFERENCES

1. C. de Silvia, *Intelligent Control – Fuzzy Logic Applications*, CRC Press, 1995.

2. M. Jamshidi, *Fuzzy Logic and Control, Software and Hardware Applications*, PTR Prentice-Hall, Inc, 1993.

3. J. Wen, S. Cheng, and O.P. Malik, "A Synchronous Generator Fuzzy Excitation Controller Optimally Designed with a Genetic Algorithm", *IEEE Trans on Power System*, Vol. 13, No. 3, August 1998.

4. Hasan, Abul R., Martis, Thomas S., Sadrul, A.H.M, "Design and Implementation of a Fuzzy Controller Based Automatic Voltage Regulator for a Synchronous Generator", *IEEE Transactions on Electrical Machinery*, Vol.9, No.6, Sep. 1994.

5. B.J. LaMeres and M.H. Nehrir, "Fuzzy Logic-Based Voltage Control of A Synchronous Generator," *IEEE Computer Applications in Power*, Vol. 12, No. 2, April 1999.

6. D.E. Goldberg, *Genetic Algorithms in Search, Optimization and Machine Learning,* Addison-Wesley, 1989.