Performance Analysis of Fuzzy Logic Controllers Optimized by Using Genetic Algorithm

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Abstract

There are many different design parameters such as membership functions, scaling factors, inference and defuzzification methods in the structures of fuzzy logic controllers. Most of the time, it is difficult to determine the parameters accurately even with the help of experts. For this purpose, genetic algorithm one of the heuristic optimization techniques is used to facilitate the design of optimal fuzzy logic controller in this study. Fuzzy logic controllers used in the studies are designed with entirely user-defined software instead of toolboxes. Performances of the designed controllers have been analyzed through simulation studies performed on the permanent magnet synchronous motor. Results obtained from the simulation studies have showed that fuzzy logic controllers optimized based on ITAE performance indice have better performance.

1. Introduction

Fuzzy logic controllers, which have a similar working structure to human thinking and decision making, have a wide using area compared to conventional control methods. Fuzzy logic controllers are widely used to control time-varying, nonlinear and complex systems, especially those whose mathematical model cannot be exactly defined.

The determination of the fuzzy logic controller parameters and the design process are usually done by trial and error method which does not have a systematic approach. Design process is based on changing the parameters of the controller designed by the experts until the desired performance level is reached. However, setting the controller parameters by manual iteration steps leads to long experiments and this takes a lot of time. In order to provide fast and efficient solutions, the fuzzy logic controller parameters are usually determined by heuristic optimization methods. Genetic algorithm is an heuristic artificial intelligence optimization method used by many researchers. Optimization of membership functions [1-3], optimization of rule table [4], reducing size of the rule base [5-6], optimization of scaling factors [7-9] and optimal controller design [10-15] are some of these studies.

In this study, the output membership functions of the fuzzy logic controller are optimized using genetic algorithm. Optimization operations were performed using three different error performance indices: integral absolute error (IAE), integral square error (ISE) and integral time weighted absolute error (ITAE). Speed control of the permanent magnet synchronous motor has been performed in the simulation studies. Performance of the controllers designed both based on the traditional methods and optimized with genetic algorithm have been analyzed and compared with each other.

The paper is organized as in five sections. Section 2 presents the fuzzy logic controller. Section 3 presents the optimization process for the fuzzy logic controller. Section 4 presents the simulation studies and performance analysis. Section 5 has the conclusions.

2. Fuzzy Logic Controller

Fuzzy logic is an artificial intelligence method first suggested by L.A. Zadeh [16]. In fuzzy logic, relations between concepts are shown linguistic quantitative expressions in verbal structure. For this reason, it is not necessary to know the mathematical model of the system worked on. Fuzzy logic controllers have three consecutive units; these are fuzzification, rule based inference and defuzzification unit respectively. Basic structure of the fuzzy logic controller is seen in Figure 1.

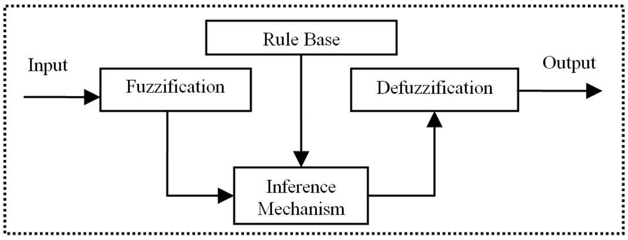

Fig. 1. Basic structure of the fuzzy logic controller

In the fuzzification unit, membership grades in the range of membership functions (0-1) corresponding to the value of the input variables are determined. In the rule based inference mechanism unit, the fuzzy values coming from the fuzzification unit are evaluated according to the verbal rules generated by the conditional statements, and then the appropriate output is associated with the membership function. Each rule in this unit provides a control that corresponds to a specific part of the system to be controlled. By using all rules together, a rule base expressing the whole system model is revealed [16-17]. In the defuzzification unit, sum of fuzzy expressions coming from the rule based inference mechanism is converted into numerical expressions that could be applied to the system.

Error and change of error values are used as input variables for the fuzzification unit. Mamdani inference method was used in rule based inference mechanism and the weighted average method was used in the defuzzification unit of the controller. The same operating structure was used for all designed controllers. All design stages of the controller subunits were implemented using user defined software.

In the optimization studies, input membership functions shown in Figure 2 are used for the designs. As shown in the Figure 2, in order to avoid any loss in data space, the sum of the values at all points along the vertical axis of the input membership functions is kept equal to one. Figure 3 shows the designed output membership functions using traditional methods. Expert person opinion has been taken into consideration when determining the intervals of the output membership functions.

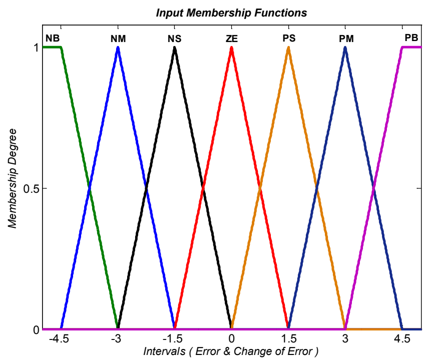

Fig. 2. Input Membership Functions

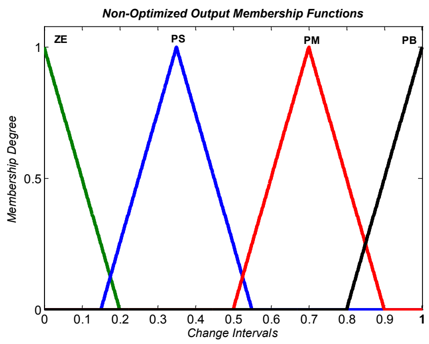

Fig. 3. Output Membership Functions Designed by Using Traditional Methods

In the designed controllers, seven different membership functions; NB(Negative Big), NM(Negative Medium), NS(Negative Small), ZE(Zero), PS(Positive Small), PM(Positive Medium) and PB(Positive Big) are used as verbal variables. The rules used for the designed fuzzy logic controller are presented in Table 1.

Table 1. Rule Table

Δe / e	NB	NM	NS	ZE	PS	PM	PB
NB	ZE	ZE	ZE	ZE	ZE	ZE	ZE
NM	ZE	ZE	ZE	ZE	ZE	ZE	PS
NS	ZE	ZE	ZE	ZE	ZE	PS	PM
ZE	ZE	ZE	ZE	ZE	PS	PM	PB
PS	ZE	ZE	ZE	PS	PM	PB	PB
PM	ZE	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

3. Optimization Process

Genetic algorithm is used for optimization processes in the study. Genetic algorithm is an optimization method based on the theory of evolution and natural selection mechanism [18-19]. Natural selection works by a mechanism based on the principle that individuals who better adapt to environmental conditions have high chances of survival and reproduction. Individuals who cannot adapt to the environmental conditions will not survive and therefore will not be able to pass on their inherited traits to the future generations.

Genetic algorithm optimization process consists mainly of the following steps [20].

i. Initial population is generated. The initial population could be generated entirely randomly or using possible solutions of the problem. Every individual in the initial population represents a possible solution for the problem.

ii. Fitness values of the all individuals in the population are calculated.

iii. Selection, crossover and mutation procedures are applied respectively. In the study, roulette wheel selection has been used for selection process and single-point crossover has been used for crossover process.

iv. Step ii and iii is repeated until the stopping criterion is satisfied. Maximum iteration number has set up for the stopping criterion in the study.

Figure 4 shows the general flow structure of the genetic algorithm.

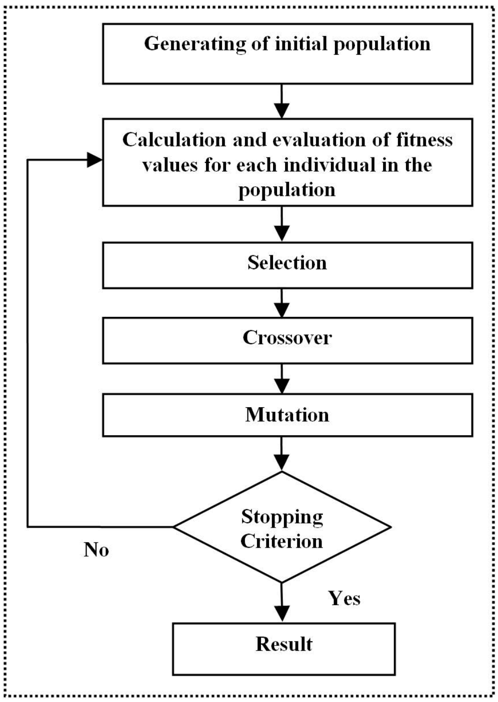

Fig. 4. Genetic algorithm flow diagram

Integral absolute error (IAE), integral square error (ISE) and integral time weighted absolute error (ITAE) performance indices have been applied for fitness function separately in the optimization studies. Mathematical equations used for these performance indices are given below.

$$IAE = \int |e(t)| dt \quad (1)$$

$$ISE = \int e^2(t) dt \quad (2)$$

$$ITAE = \int t|e(t)| dt \quad (3)$$

Parameters used for the genetic algorithm are seen in the Table 2. Properly choosing of the parameters directly affects performance of the optimization process. While a correct selection ensures that other successful points can be tested on the road until the desired target zone is reached during the optimization process, a wrong selection can cause unexpected movements by deviating from the desired target zone during the optimization process.

Table 2. GA Parameters

Parameter	Value
Population Size	40
Iteration Number	100
Problem Size	4
Crossover Rate	0.9
Mutation Rate	0.005
Boundaries	[0-1]

It is aimed to optimize output membership functions in optimization studies. In the genetic algorithm, individuals in the population represent the center of gravity of the output membership functions to be optimized. Areas of membership functions that are optimized according to the used error performance indice during the iterations are also automatically updated. Optimization studies were performed with permanent magnet synchronous motor's (PMSM) circuit built on MATLAB / Simulink platform under loaded operating conditions. Parameters of the PMSM that used in studies: Rs=0.96Ω, Ld=Lq=0.00525H, B=0.0003035Nms, J=0.00064kgm/s², ψm=0.1827Wb, p=4. Optimization process schematic used in the studies is shown in the Figure 5.

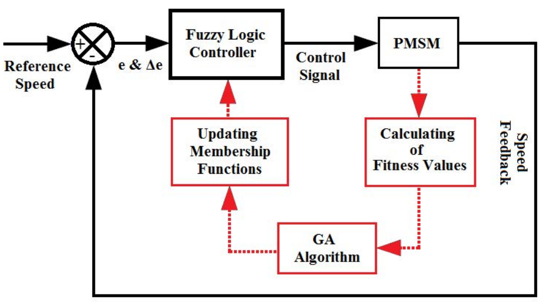

Fig. 5. Optimization schematic

Where, e denotes error and Δe denotes change of error values. In the iterations, firstly the fitness values are calculated according to the performance indice used for the optimization. Best values are determined from the fitness values in the population by using genetic algorithm. The solution values that provide the most successful results represent the output membership functions that will be used for the next iteration.

The optimized output membership functions are shown in the graphs in Figure 6-8 respectively.

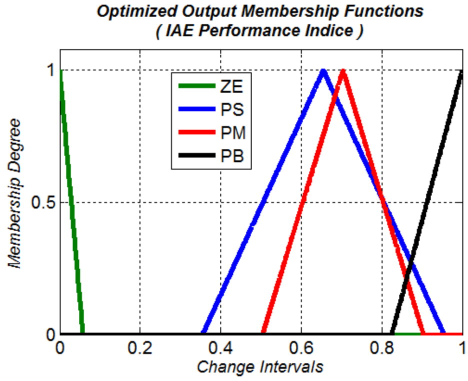

Fig. 6. Change intervals of the output membership functions optimized with IAE indice

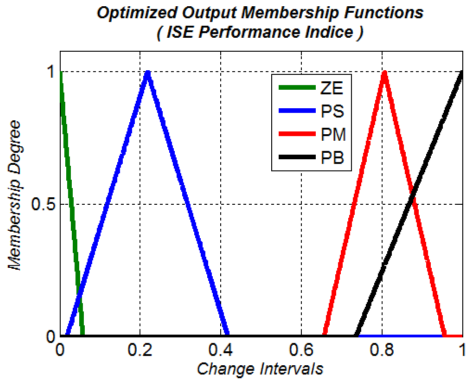

Fig. 7. Change intervals of the output membership functions optimized with ISE indice

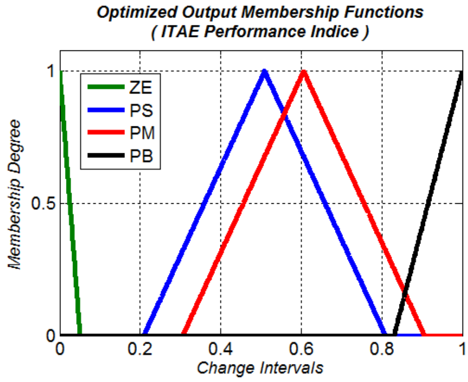

Fig. 8. Change intervals of the output membership functions optimized with ITAE indice

4. Simulation Studies and Performance Analysis

Speed control performance and torque variations of PMSM were investigated in the simulation studies under loaded operating conditions. Simulation studies were performed with PMSM under 300 rad/s reference speed and 5Nm load operating conditions using fuzzy logic controllers that are optimized based on different performance indices. Speed control performances of the fuzzy logic controllers (FLC) constituted with optimized and non-optimized output membership functions are seen in the Figure 9.

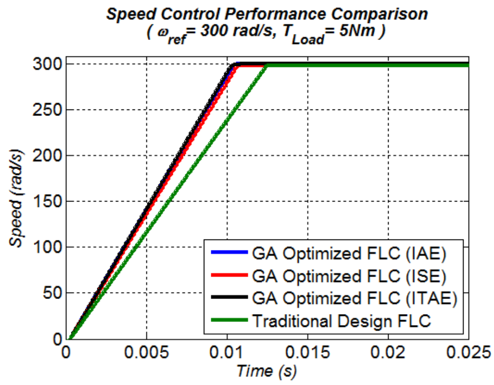

Fig. 9. Speed control performance comparisons

When the speed control comparison graphs in the Figure 9 are examined, it is seen that optimized controllers provide more successful results compared to the controllers designed with traditional methods in terms of performance criteria like as rise time, settling time, maximum overshoot and steady state error values. In the Figure 10-12, torque variations of the controllers designed both based on the traditional methods and optimized with genetic algorithm are seen.

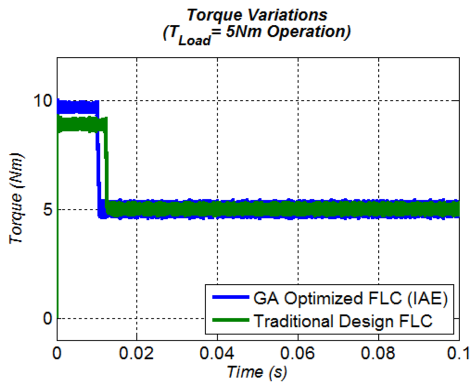

Fig. 10. Torque variations for the controllers optimized with IAE indice

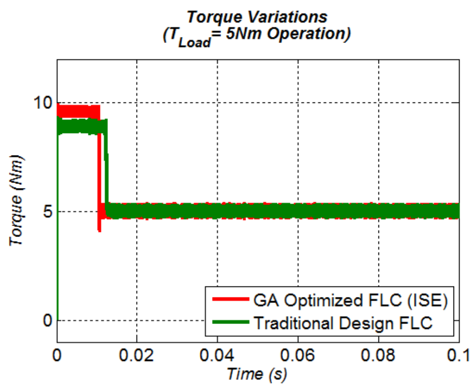

Fig. 11. Torque variations for the controllers optimized with ISE indice

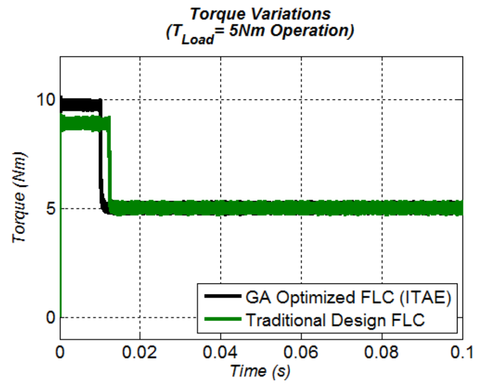

Fig. 12. Torque variations for the controllers optimized with ITAE indice

If the torque graphs are evaluated, it can be seen that the most successful results in terms of torque ripples are obtained with the controller optimized according to the ITAE performance indice. Since the slope of the motor's acceleration process is constant, the torque values remain constant until the speed is reached to reference value. Once the motor has reached the reference speed, it produces a torque equal to the load.

5. Conclusions

In this study, fuzzy logic controller was optimized according to different performance criteria with genetic algorithm and accordingly simulation studies were made. Performance comparisons of the designed controllers are shown in Table 3 and 4.

Table 3. Comparisons of controllers based on time zone performance criteria

Performance Criterion / **Performance Indice**	Rise Time	Settling Time	Steady State Error
IAE	8.496 *ms*	10.62 *ms*	0.17 *rad/s*
ISE	8.676 *ms*	10.83 *ms*	2.46 *rad/s*
ITAE	9.357 *ms*	10.59 *ms*	0.64 *rad/s*
Traditional Design	10.062 *ms*	12.53 *ms*	2.08 *rad/s*

Table 4. Comparisons of speed and torque ripples for the designed FLC controllers

Comparison Parameter / **Designed Controllers**	Speed Ripple Band	Torque Ripple Percentage
IAE - FLC	0.04 *rad/s*	%6.527
ISE - FLC	0.022 *rad/s*	%5.624
ITAE - FLC	0.02 *rad/s*	%4.284
Traditional Design - FLC	0.0185 *rad/s*	%5.177

When the values in Table 3 and 4 are examined, it is seen that the speed ripples and torque ripple percentages perform in an interrelated manner. ITAE performance indice which have most successful results for performance criteria is also provide the best results in terms of speed and torque ripples. When the optimization results based on the ITAE criterion were evaluated, results were obtained with %17 less torque ripples than the traditional design.

In this performed study, it is ensured that optimum fuzzy logic controller designs can be made by using genetic algorithm, in this way faster solutions can be obtained by reducing the need for expert person. It is planned to test the current work in the application environment.

6. Acknowledgment

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