BLOCK BASED FUZZY CONTROLLERS

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ABSTRACT

Fuzzy control has been widely used in industrial controls, particularly in situations where conventional control design techniques have been difficult to apply. Number of fuzzy rules is very important for real time fuzzy control applications. This paper proposes a novel approach called block based fuzzy controllers. This study is motivated by the increasing need in the industry to design highly reliable, efficiency and low complexity controllers. The proposed block based fuzzy controller is constructed by several fuzzy controllers with less fuzzy rules to carry out control tasks. Performances of the proposed fuzzy controller are investigated and compared to those obtained from the conventional fuzzy controller. For this reason, a position control problem of dc motor and a speed control problem of vector controlled induction motor are chosen. With low computational complexity, simulation results show that the proposed block based fuzzy controllers effectively control the system.

Keywords: *Fuzzy control; Block based fuzzy controller; Reduce of rule base; DC motor; Vector control*

1. INTRODUCTION

Fuzzy control has gained very much interest in recent years [1-3]. A number of successful applications have been reported in the literature and these applications of the fuzzy control to industrial processes have often produced results superior to those of classical control [4-7]. This increased popularity of the fuzzy control can be attributed to the fact that fuzzy logic systems provide a powerful vehicle that allows engineers to incorporate human reasoning in the control algorithm. The fuzzy logic system design is not based on the mathematical model of process. The fuzzy controllers designed using fuzzy logic implements human reasoning that has been programmed into membership functions, fuzzy rules and rule interpretation. The fuzzy logic controller involves four main stages: fuzzification, rule base, inference mechanism and defuzzification as shown in figure 1. The fuzzification and the defuzzification stages are needed to convert and reconvert real world crisp signals into fuzzy values and vice versa. The inference mechanism determines the matching degree of the current fuzzy input with respect to each rule and decides which rules are to be fired according to the input field. Next, the fired rules are combined to form the control actions [8].

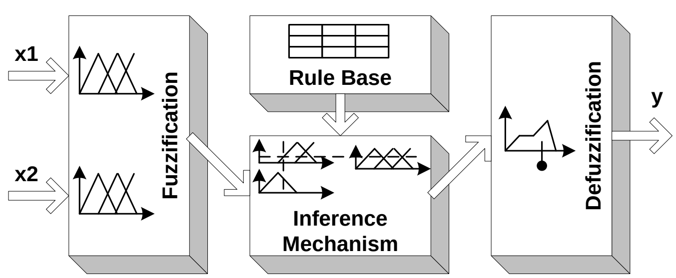


Figure 1. *Structure of a fuzzy controller*

Fuzzy controllers are able to make effective decisions on the basis of linguistic information. Recent developments in fuzzy theory offer several effective methods for the design and tuning of fuzzy controllers [9, 10, 25]. Most of these developments reduce number of fuzzy rules. Because implementation of fuzzy controllers require a large computational time for each step time in order to compute the appropriate control value to be applied to the system. Therefore, a reduction of the large fuzzy rule base is required.
A number of studies have been proposed for fuzzy rule base reduction in the literature [11-18]. Bezine [11] concerned with an automatic generation method of the fuzzy rule base and treats the reduction of large scale fuzzy rule bases using the boolean method and the decoupling approach giving a local control loop yielding smaller fuzzy controllers. Ciliz [12] proposed a rule base reduction and tuning algorithm as a design tool for the fuzzy control of

vacuum cleaner. Song [16] proposed a rule base reduction method for Takagi-Sugeno type fuzzy logic controllers. A search algorithm finds parameters in rule output functions and it is trained for reduction. Tao [17] presented an approach to reducing the number of rules of the fuzzy controllers. In this study, the output consequents in the cells of the rule table are collected and represented as an output consequent matrix and then the feature of the output consequent matrix is extracted by the singular values of the matrix. In [19], a singular value based method is given to reduce a fuzzy rule set. This method conducts singular value decomposition of the rule consequents and generates certain linear combinations of the original membership functions to form new ones for the reduced set. Reference [20] concentrates on the reduction technique that is rather independent from the style of the interpolation model, but cannot be given in the form of a tractable algorithm. These approaches in the literature are complex and it requires additional computation time.

In this study, the block based fuzzy controllers are proposed to reduce number of fuzzy rules. This novel controller uses several fuzzy controllers which has smaller fuzzy rule base than rule base of the conventional fuzzy controller.

2. THE CONVENTIONAL FUZZY CONTROLLERS

Fuzzy control uses the principles of fuzzy logic based decision making to achieve the control tasks. The decision making approach is typically based on rule of inference. A fuzzy rule in the knowledge base of the control task is generally a linguistic relation. We have a rule base with a set of the rule form as follows.

IF Ai AND Bi THEN Ci

The overall membership function for the complete rule base can be obtained as,

$$\mu(a,b,c) = \max\ \min\left[\mu_A(a), \mu_B(b), \mu_C(c)\right]$$

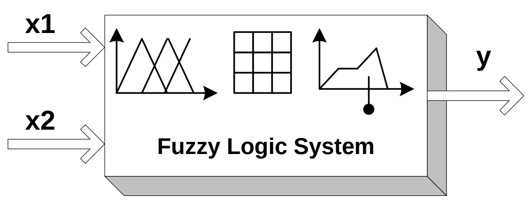


Figure 2. *A fuzzy logic system*

Figure 2 shows the block diagram of a conventional fuzzy logic system with two input and one output variables. The fuzzy logic systems are used as a controller with various control schemes. The most obvious one is shown in figure 3, where the fuzzy controller is in the forward path in a feedback control system. The process output is compared with a reference, and if there is a deviation, the controller takes action according to the control strategy.

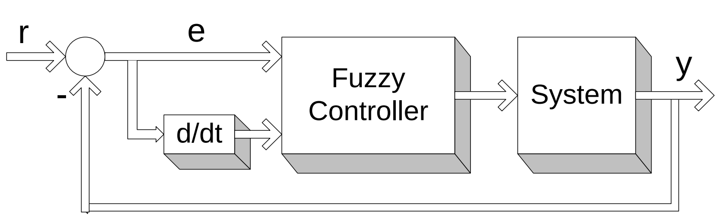
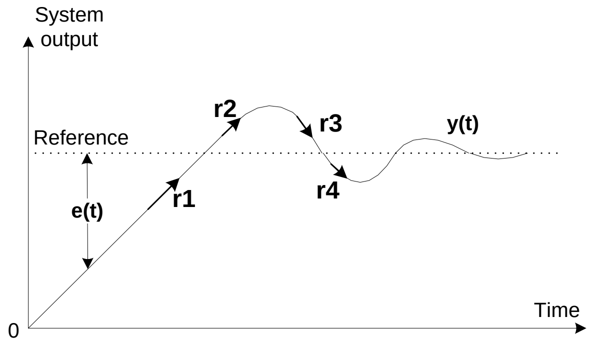
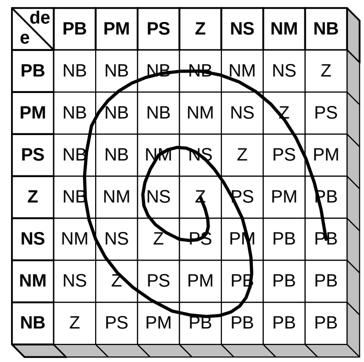


Figure 3. *The control system structure with a fuzzy controller*

Let r be the desirable output of system, the error e between desirable output and the response system can be given as e=r-y.



(a)



e \ de	PB	PM	PS	Z	NS	NM	NB
PB	NB	NB	NB	NB	NM	NS	Z
PM	NB	NB	NB	NM	NS	Z	PS
PS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
NS	NM	NS	Z	PS	PM	PB	PB
NM	NS	Z	PS	PM	PB	PB	PB
NB	Z	PS	PM	PB	PB	PB	PB

(b)

Figure 4. *Output response of a controlled system*

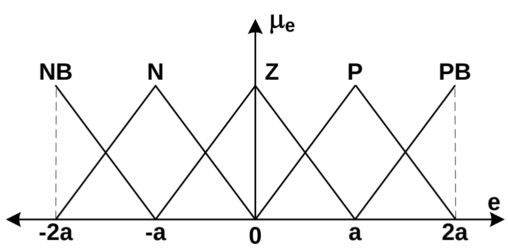
The typical behavior of a controlled system is shown in figure 4(a). It can be divided into several regions as r1, r2, r3, r4. Then, some relations are given as:

$$e > 0 \Rightarrow e = r - y > 0 \Rightarrow r > y \Rightarrow \text{r1 or r4} \qquad \dot{e} < 0 \Rightarrow \dot{e} = \dot{r} - \dot{y} = 0 - \dot{y} \Rightarrow \dot{y} > 0 \Rightarrow \text{r1 or r2}$$

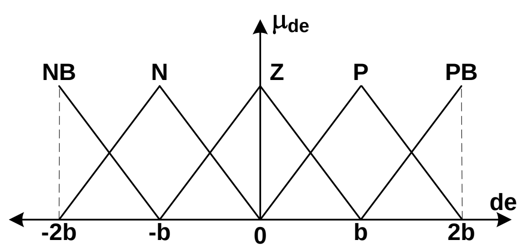
$$e < 0 \Rightarrow e = r - y < 0 \Rightarrow r < y \Rightarrow \text{r2 or r3} \qquad \dot{e} > 0 \Rightarrow \dot{e} = \dot{r} - \dot{y} = 0 - \dot{y} \Rightarrow \dot{y} < 0 \Rightarrow \text{r4 or r3}$$

Figure 4(b) shows the fuzzy rule base created by these relations. If a trajectory on the rules table for a stable system is drawn, the error and the change in error should be gradually decreased during the rules firing process. There is an inverse tendency for an unstable system [13].

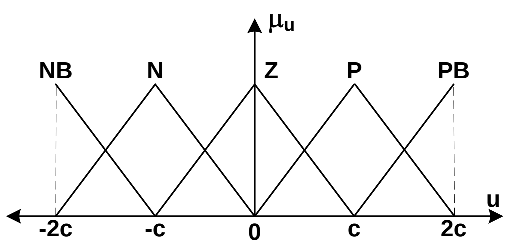
As well known, a fuzzy controller uses generally error and change in error as input variables. In many systems, the membership functions and the rule base of a fuzzy controller can be used in general forms as shown in figure 5. Five triangular membership functions have been used for two inputs as in figure 5(a, b). Five or seven membership functions can be used for output of fuzzy controller as in figure 5(c1, c2). The fuzzy controller has 25 fuzzy rules as shown in figure 5(d1). If seven membership functions are used for output variable, the rule base can be given as in figure 5(d2). Figure 5(e1, e2) shows surface view of fuzzy controller for which used rule bases are given in figure 5(d1, d2).



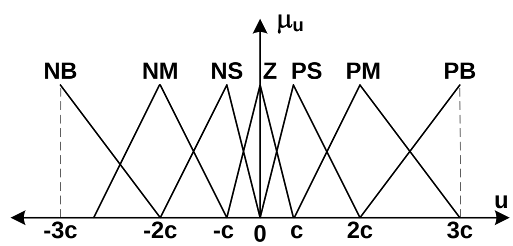
***(a)** Input variable "error"*



***(b)** Input variable "change in error"*



***(c1)** Output variable "action" with 5 membership functions*



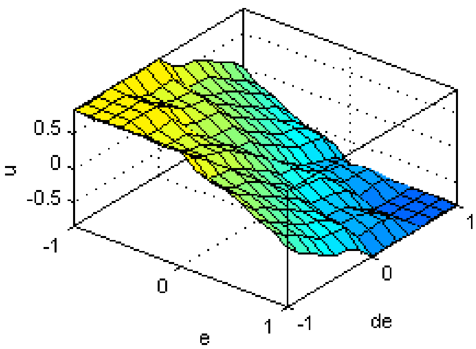
***(c2)** Output variable "action" with 7 membership functions*

de \ e	NB	N	Z	P	PB
NB	PB	PB	PB	P	Z
N	PB	PB	P	Z	N
Z	PB	P	Z	N	NB
P	P	Z	N	NB	NB
PB	Z	N	NB	NB	NB

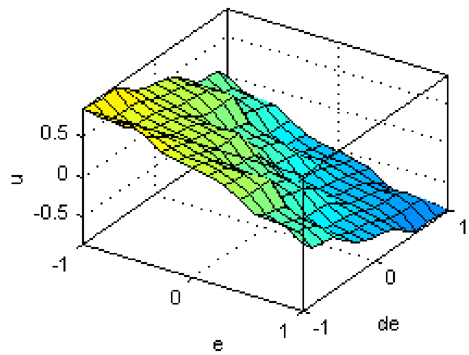
(d1) *Rule base for (c1)*

de \ e	NB	N	Z	P	PB
NB	PB	PB	PM	PS	Z
N	PB	PM	PS	Z	NS
Z	PM	PS	Z	NS	NM
P	PS	Z	NS	NM	NB
PB	Z	NS	NM	NB	NB

(d2) *Rule base for (c2)*



(e1) *Surface view for (d1)*



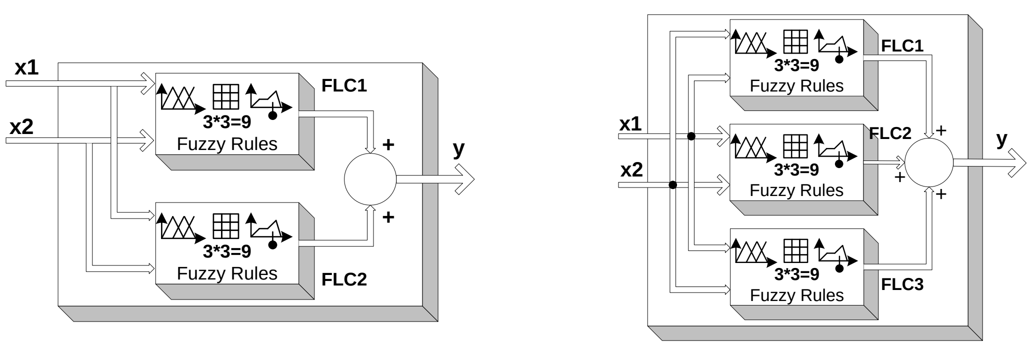
(e2) *Surface view for (d2)*

Figure 5. *Membership functions, rule base and surface view of a conventional fuzzy controller*

3. PROPOSED BLOCK BASED FUZZY CONTROLLERS

Number of fuzzy rules is an important issue in fuzzy controller design, especially for real time applications. For control applications, often there is no enough data for a designer to create the rule base for the fuzzy controller. Therefore, a designer has to build a general rule base. A general rule base includes all possible combinations of fuzzy input values. The size of fuzzy rule base grows exponentially as the number of controller input grows. A complete rule base for the fuzzy controller with n inputs and m membership functions per input will result in m^n rules. Therefore the rule base reduction is very important for the fuzzy controller in the control applications. The precision of the fuzzy controller can be achieved by using 5, 7 or 9 membership functions at the inputs. Most of the membership functions can be assigned around the zero value to achieve higher precision. For better precision, the number of membership functions can be increased at the expense of computational cost.

The fuzzy controller structures are showed in figure 6(a, b) called as block based fuzzy controller with several fuzzy controllers which has very small rule base. Inputs of blocks are error and change in error for a controller. However this structure can be also use general fuzzy systems with different inputs and outputs.



(a) **(b)**

Figure 6. *Schemes of block based fuzzy controller*

The block based fuzzy controller proposed in this study consists of the sum of two or more fuzzy controller with a small rule base. The most suitable fuzzy controller with a small rule base includes three membership functions for each input. As shown in figure 7(a, b, c), the block based fuzzy controller with two blocks has the membership functions that are different base values. If base values of membership functions of the conventional fuzzy controller changes in range [-2a, 2a] and the block based fuzzy controller consists of two small fuzzy controllers, then the base values of the first fuzzy controller change in range [-2a, 2a] and the base values of the second fuzzy controller change in range [-a, a]. If it consists of three small fuzzy controllers, the base values of the third fuzzy controller change in range [-a/2, a/2]. The rule base of each small fuzzy controller in the block based fuzzy controller is same. Figure 7(a-e) shows the membership functions, rule table and surface view of flc1 and flc2 for the block based fuzzy controller in figure 6a.

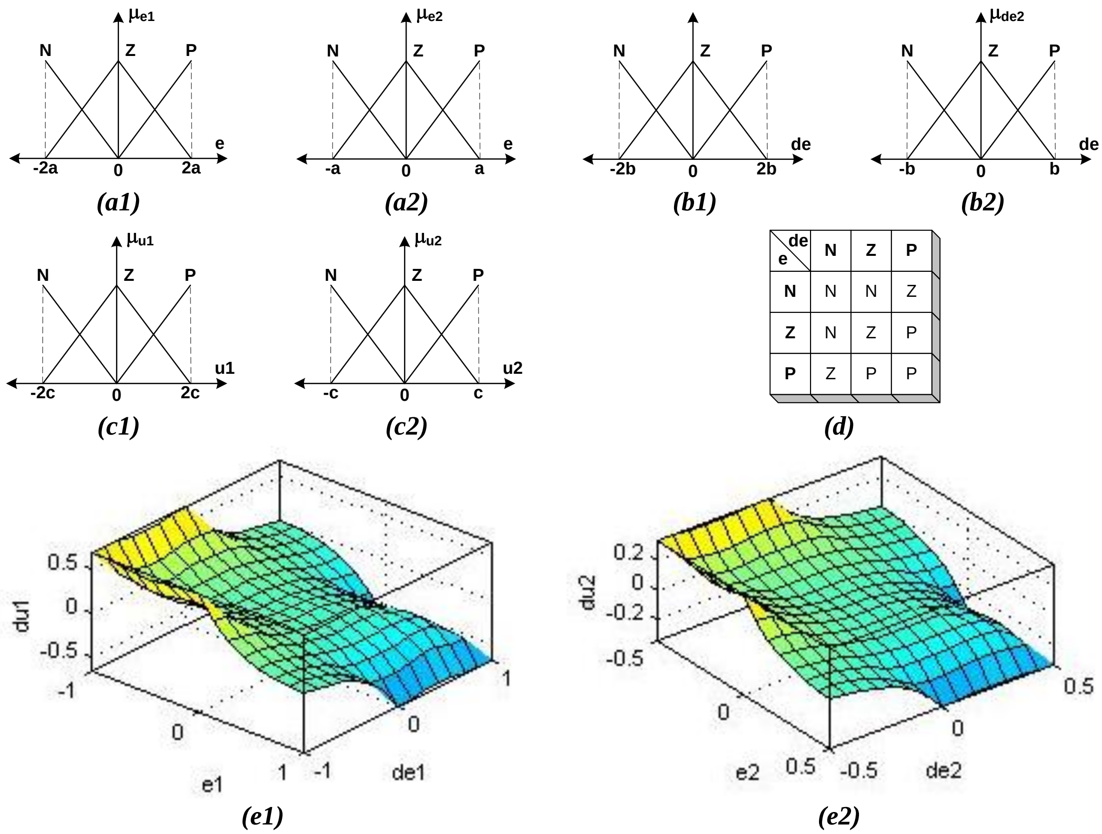


Figure 7. *Membership functions, rule base and surface view for proposed block based fuzzy controllers*

Table 1. *Sample combinations for base values of fuzzy controllers*

5*5 or 7*7 Fuzzy Controller		Block Based Fuzzy Controller					
		1. Block		2. Block		3. Block	
Inputs	Outputs	Inputs	Outputs	Inputs	Outputs	Inputs	Outputs
[-2x, 2x]	[-2y, 2y]	[-2x, 2x]	[-2y, 2y]	[-x, x]	[-y, y]	-	-
“	“	“	“	“	[-2y, 2y]	-	-
[-2x, 2x]	[-2y, 2y]	[-2x, 2x]	[-2y, 2y]	[-x, x]	[-y, y]	[-x/2, x/2]	[-y/2, y/2]
“	“	“	“	“	[-2y, 2y]	“	[-2y, 2y]
[-2x, 2x]	[-2y, 2y]	[-2x, 2x]	[-2y, 2y]	[-x/2,x/2]	[-y/2, y/2]	-	-
“	“	“	“	“	[-2y, 2y]	-	-
[-2x, 2x]	[-2y, 2y]	[-2x, 2x]	[-2y, 2y]	[-x/2,x/2]	[-y/2, y/2]	[-x/4,x/4]	[-y/4, y/4]
“	“	“	“	“	[-2y, 2y]	“	[-2y, 2y]
…	…	…	…	…	…	…	…

Different structures with different base values can be used according to the system. Sample combinations of the block based fuzzy controllers are given in table 1. The block based fuzzy controller with two blocks can be generally used in many systems because of it will provide performance of typical fuzzy controllers.
Table 2 shows number of rules and membership functions, computational time of proposed block based fuzzy controllers and typical fuzzy controllers. Computational times in table 2 have been obtained with a digital signal processor. This digital signal processor is a Texas Instruments TMS320C31 32-bit floating-point processor with a 60 ns instruction cycle [21]. As shown in table 2, the computational time of the block based fuzzy controller with two blocks is very low according to the conventional fuzzy controllers. Therefore, the block based fuzzy controllers is very suitable for real time applications.

Table 2. *The computational complexity of fuzzy controllers*

	Block based fuzzy controller	5*5 fuzzy controller	7*7 fuzzy controller
Number of fuzzy rules	9	25	49
Number of membership functions	9+9=18	15	21
	9+9+9=27		
Total time with digital signal processor	~ 15-22 μs	~ 30 μs	~ 65 μs

4. SIMULATION RESULTS

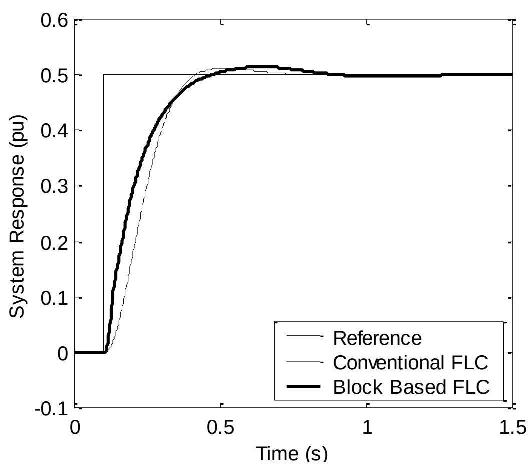
Firstly output responses of the proposed block based fuzzy controller with three blocks and conventional fuzzy controller were analyzed for random error (e) and change in error (de) values. Complete fuzzy controllers were developed using Matlab Fuzzy Logic Toolbox.

Example 1: Position Control of DC Motor

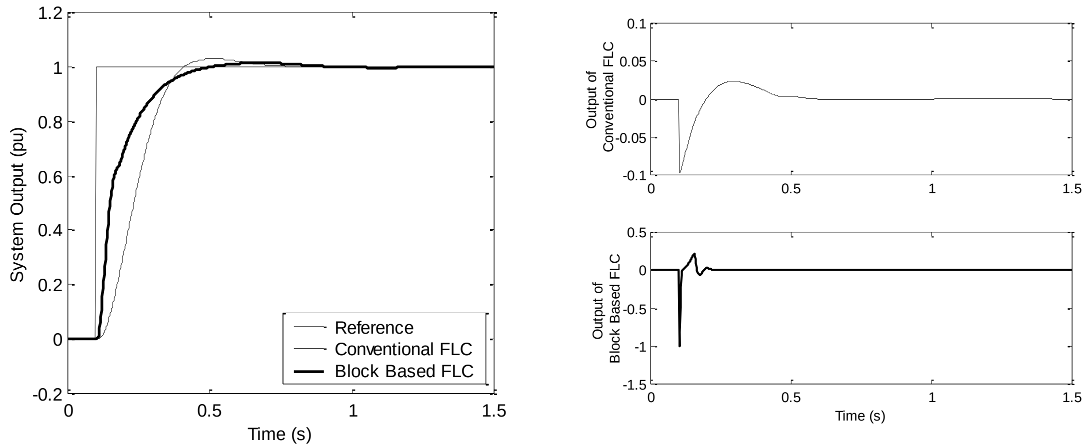
Performance of the proposed block based fuzzy controllers was investigated by means of simulations in the MATLAB/Simulink [22]. In order to analyze behavior of fuzzy controllers, we chose to use a position control problem of dc motor. A transfer function can be given as:

$$G(s) = \frac{2.2}{s(8.6\times10^{-6}s^2 + 7.3\times10^{-3} + 0.95)}$$

As shown in figure 8(a) and 8(b1), the block based fuzzy controller gives approximately same system response with conventional fuzzy controller. Figure 8(b2) shows output of both controllers. Figure 9(a) and 9(b) show the system response and the output behavior of the conventional fuzzy controller and the block based fuzzy controllers which have 2 and 3 rule base. Results for different references are shown in figure 10. In all of the simulations, the conventional fuzzy controller has 49 rules. The performance of the block based fuzzy controller is maintained by using two fuzzy controllers with 9 rules.

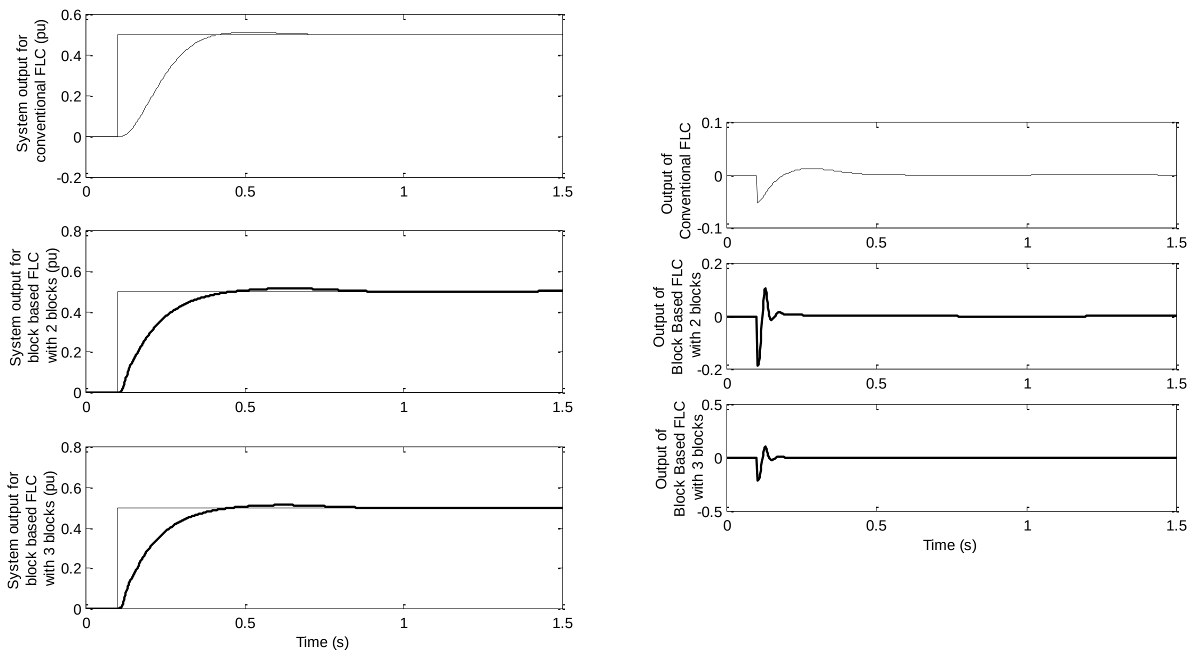


(a)



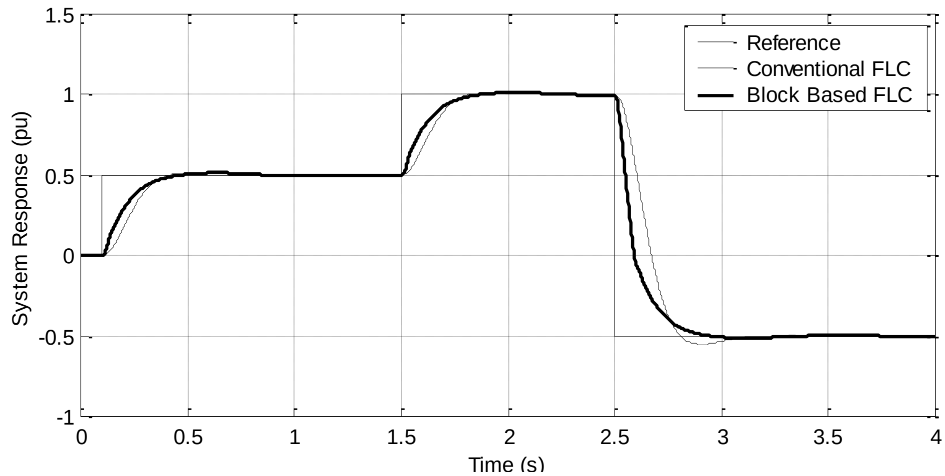
(b1) ***(b2)***

Figure 8. ***(a)*** *System output for conventional fuzzy controller and block based fuzzy controller for 0.5 pu reference,* ***(b1)*** *System output for conventional fuzzy controller and block based fuzzy controller for 1 pu reference,* ***(b2)*** *Output response of conventional fuzzy controller and block based fuzzy controller for 1 pu reference.*

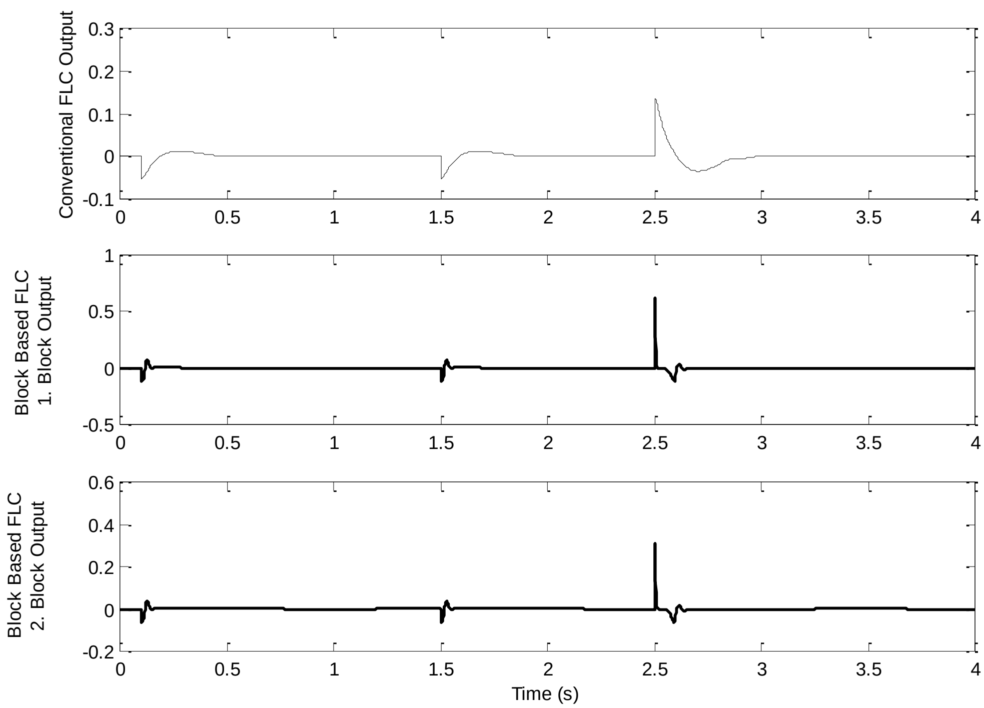


(a) ***(b)***

Figure 9. ***(a)*** *System output for conventional fuzzy controller and different block based fuzzy controllers,* ***(b)*** *Output response of conventional fuzzy controller and different block based fuzzy controllers*



(a)



(b)

Figure 10. ***(a)*** *System output for conventional fuzzy controller and block based fuzzy controller for different references* ***(b)*** *Output response of conventional fuzzy controller and block based fuzzy controller for different references*

Example 2: Speed Control of Vector Controlled Induction Motor

Speed control of vector controlled induction motor was chosen as another example to show performance of fuzzy controllers. The block diagram of the implemented vector controlled drive is shown in Fig 11. To compare performance of controllers, the block based fuzzy controller and conventional fuzzy controller were used instead of controller block in figure 11.

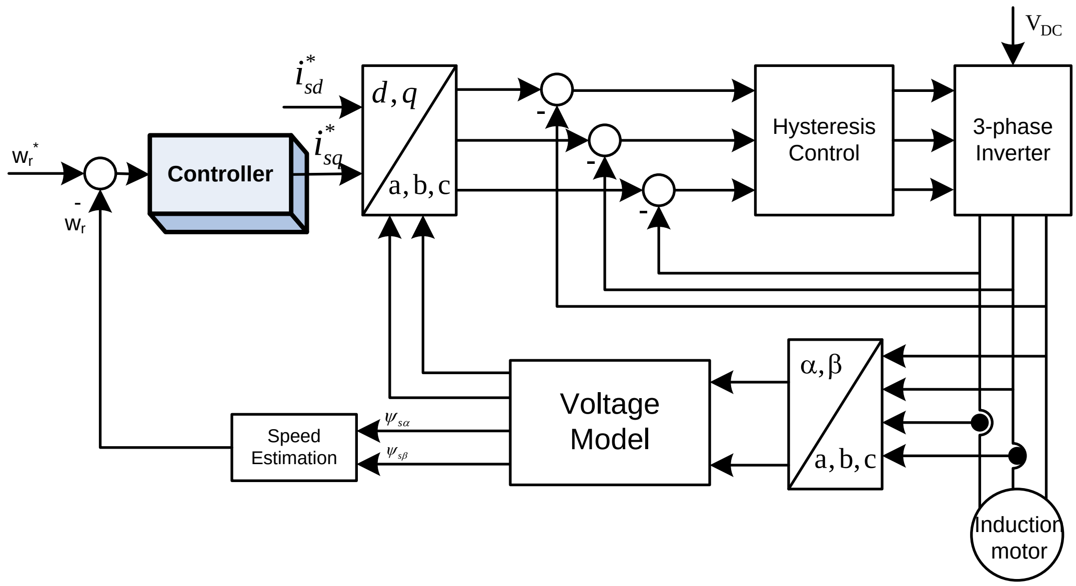
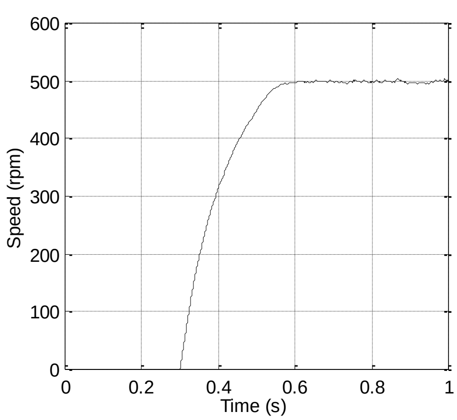
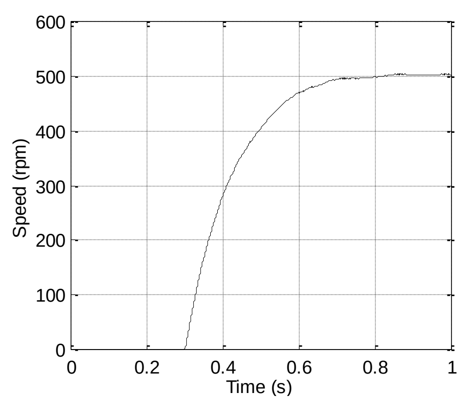


Figure 11. *Block diagram of vector controlled induction motor*

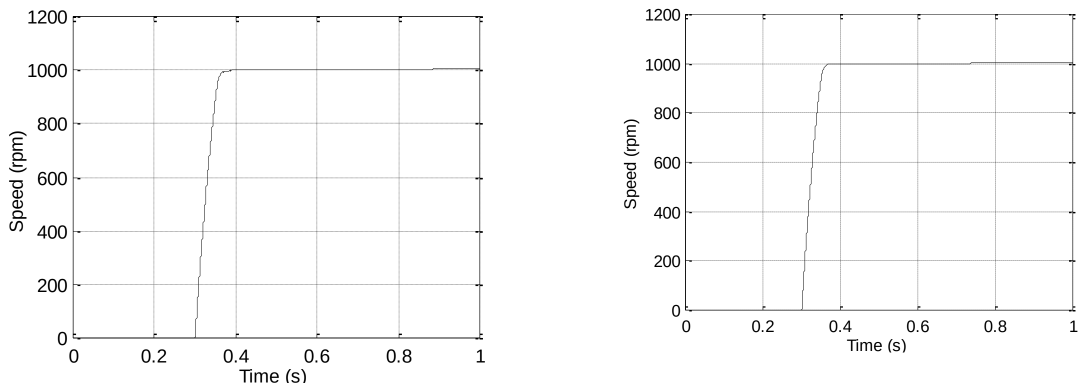
Vector control of induction motor is very complex and nonlinear [23, 24]. Therefore, speed control problem of vector controlled induction motor was chosen for comparison of fuzzy controllers. Some simulation results were obtained for different speed references. As shown in figure 12, speed responses are given for 500 and 1000 rpm speed references. Figures 12(a1, b1) show speed responses of induction motor with the proposed block based fuzzy controller and figures 12(a2, b2) show speed responses of induction motor with the conventional fuzzy controller. As shown in figure 12, the results obtained from block based fuzzy controller with two blocks (only 9 rules) are better than the results of conventional fuzzy controller with 49 fuzzy rules.



(a1)



(a2)



(b1) ***(b2)***

Figure 12. *Speed responses of vector controlled induction motor in different speed references using block based fuzzy controller (a1-b1) and conventional fuzzy controller (a2-b2)*

As shown in all results for both position control of dc motor and speed control of vector controlled induction motor, performance of the block based fuzzy controller is approximately same or better than performance of the conventional fuzzy controller. In the results, the system output with the block based fuzzy controller rises to reference faster than the system output with the conventional fuzzy controller. The settling time and the overshoot of system response with the block based fuzzy controller are generally same with system response with the conventional fuzzy controller.

5. CONCLUSIONS

A novel fuzzy controller structure called the block based fuzzy controllers is proposed for the development of the knowledge based fuzzy controllers. The development structure is especially for real time applications of fuzzy logic theory. The computational time of the conventional fuzzy controller can be reduced by 50 percent using the block based fuzzy controllers. Implementation of the block based fuzzy controllers is very easy. Simulation results are given for the control of a dc motor and vector controlled induction motor drive to demonstrate the efficient use of the proposed block based fuzzy controller.

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