The Experiment and Simulation Results of Speed Control of Permanent Magnet Synchronous Motor by Using Fuzzy Controller

Aykut Teker[1] and F. Erfan Kuyumcu[2]

[1]Siemens Sanayi ve Ticaret Anonim Sirketi, Yakacik Caddesi No:111, 34870
Istanbul, Turkey
aykut.teker@siemens.com

[2]Istanbul Gedik University, Engineering Faculty, Electrical-Electronic Engineering Department,
Kartal, Turkey
feriha.kuyumcu@gedik.edu.tr

Received: 28.11.2018 Accepted: 25.12.2018

Abstract – This paper is concerned with the topics on the speed control of Permanent Magnet Synchronous Motor (PMSM) with using Matlab/Simulink in real system. The speed control of motor model is done with Fuzzy Logic controller. The Simulation and experimental results of controller performances are compared with the speed graphs obtained.

Keywords: Fuzzy control, permanent magnet synchronous motor, simulation, experimental, application.

1. INTRODUCTION

The PM Synchronous motors are being increasingly used in a wide range of applications because of their high power density and efficiency. In the classical control, most of the automatic control problems are usually solved by mathematical tools based on the system model but in the real world, there are many complexes industrial processes whose real models can't be easily developed. Hence, a fuzzy logic controller using linguistic information applies to the model the qualitative aspects of human knowledge, providing an alternative to conventional control techniques [2].

In this paper, fuzzy control is used for speed control of PM synchronous motor. Experiment and simulation results of controller performances are compared with graphs obtained. For speed control method, a fuzzy logic using error and derivative of error inputs is proposed. The basis of the development of the fuzzy logic controller is the analysis of the PMSM transient response and fuzzy logic. The fuzzy controller generates the variations of the reference current vector of the PMSM speed control based on the speed error and its change. The results of experiment and simulation show that the fuzzy controller can be used in sensitive application. This application of fuzzy logic to automation and control engineering represents a logical extension of traditional control technology [1].

2. MATHEMATIC MODEL OF PMSM BY MATLAB / SIMULINK

The stator of the PMSM and the wound rotor synchronous motor (SM) are similar. In addition there is no difference between the back electromotive force (emf) produced by a permanent magnet and that produced by an excited coil. Hence the mathematical model of a PMSM is similar to that of the wound rotor SM. The following assumptions are made in the derivation: Saturation is neglected although it can be taken into account by parameter changes, the back EMF is sinusoidal, eddy currents and hysteresis losses are negligible. The parameters of PM Synchronous Motor are given in the Table I.

Table 1. Parameters of PM Synchronous Motor.

Parameters	Description	Value
Rs	Stator phase resistance (Ω)	10.4
p	Number of poles per phase	4
Ld	d-axis Inductance (mH)	43
Lq	q-axis Inductance (mH)	43
λm	Magnetic Flux Linkage (Wb)	0.1
J	Inertia (kgm)	$0.94*10^{-4}$
B	Flux Density (Nmsrad)	≈0

Motor model is constituted of following equations:

$$T_e = \frac{3}{2} \cdot \frac{p}{2} \left[\lambda_m i_q + (L_d - L_q) i_d i_q \right] \tag{1}$$

$$\frac{d(i_d)}{dt} = \frac{V_d - R_s i_d + \omega_r L_q i_q}{L_d} \tag{2}$$

$$\frac{d(i_q)}{dt} = \frac{V_q - R_s i_q + \omega_r L_d i_d + \lambda_m}{L_q} \tag{3}$$

$$\frac{d(\omega_{rm})}{dt} = \frac{T_e - T_L - B\omega_{rm}}{J} \tag{4}$$

Where T_L is the load torque, B is the viscous frictions, J is the moment of inertia, V_d and V_q represent the d-q axes stator voltages, i_d and i_q are d-q axis stator inductances, Rs is the per phase stator resistance, ω_r shows the electrical velocity of the rotor. λ_m is expression of the flux linkage due to the rotor magnets linking the stator, T_e is the motor produced torque and ω_{rm} is the mechanical velocity of the rotor. For this study, real parameters of machine are used as given Table I. The results of this simulation can be compared with the results of the real experiment.

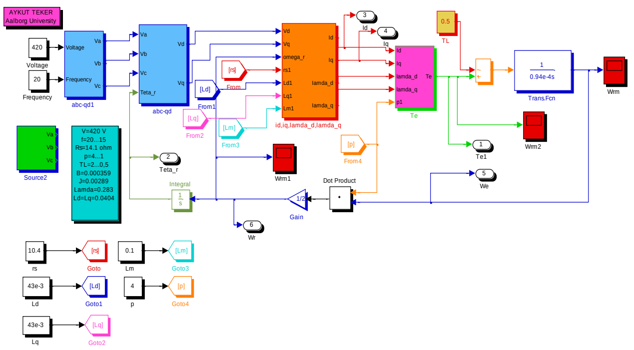


Figure 1. Mathematics model of PMSM.

2.1. Control Strategies

The PM Synchronous motor is a rotating electric machine where the stator is a classic three phase stator as an induction motor and the rotor has surface-mounted permanent magnets. In this respect, the PMSM is equivalent to an induction motor in which the air gap magnetic field is produced by a permanent magnet. The use of a permanent magnet to generate a substantial air gap magnetic flux makes it possible to design highly efficient PM motors.

The rotor speed ω_r is compared with the reference speed ω_r^* and the resulting error is processed in the fuzzy speed controller for each sampling interval. For low speed operation of PM motors the flux weakening effect is not required, however the effect of flux weakening is observed for the high speed operation of PMSM. Hence in this analysis, the direct axis reference current i_d^* is considered to be zero for low speed operation.

The d-q axis reference currents i_d^* are used to generate the reference currents i_a^*, $i_b^*$and i_c^* in the reference current generator. The reference currents have the shape of sinusoidal wave in phase with respective back emf to develop a constant and unidirectional torque. In PWM current regulating block, the motor winding currents are compared with the reference currents and the switching commands are generated for the inverter devices. In the case of sinusoidal fed PM motor, the orientation of the stator current gives a highly desirable characteristic. By neglecting the flux weakening effect for the low speed operation of the motor, the reference direct axis current (i_d^*) becomes zero.

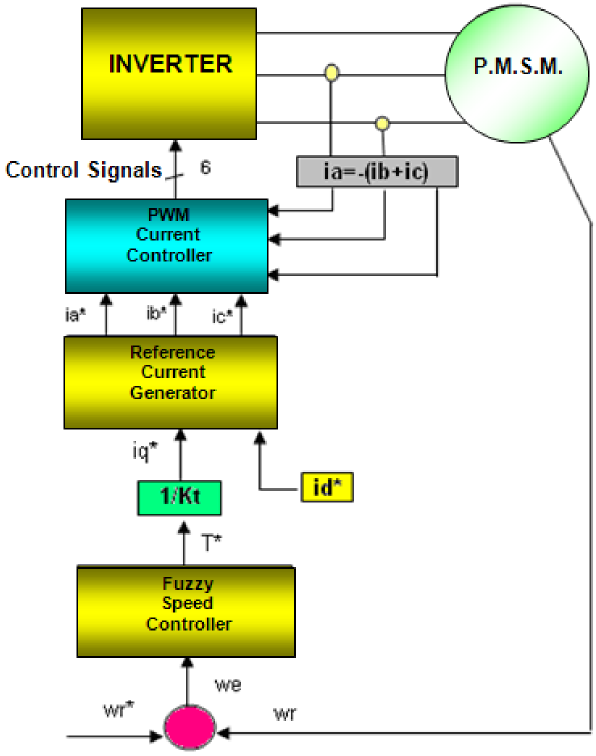


Figure 2. Schematic block diagram of Fuzzy controlled PMSM drive.

2.2. Fuzzy Controller Structure

The kind of a structure that a fuzzy controller will have will primarily depend on the controlled process and demanded quality of control. Since the application area for fuzzy control has widely use, there are many possible controller structures, some differing significantly from each other by the number of inputs and outputs, or less significantly by the number of input and output fuzzy sets and their membership functions forms, or by the form of control rules, the type of inference engine, and the method of defuzzification [3].

All that variety is the designer's disposal, and it is up to the designer to decide which controller structure is optimal for a particular control problem. The basic structure of a fuzzy controller is shown in Figure 3. Although there are many analog fuzzy controllers on the market, most of today's fuzzy controllers are implemented in digital form. This is the reason why the term B/F conversion is introduced here as inputs of a digital fuzzy controller are defined over discrete universes of discourse with the finite number of elements (integers) obtained after quantization of sensor signals. Fuzzy controller has a disadvantage. The amount of rule base of the fuzzy controller is bigger when the sensitivity of the output is high, and how to reduce memory capacity is crucial [1].

 ISSN: 2651-5199

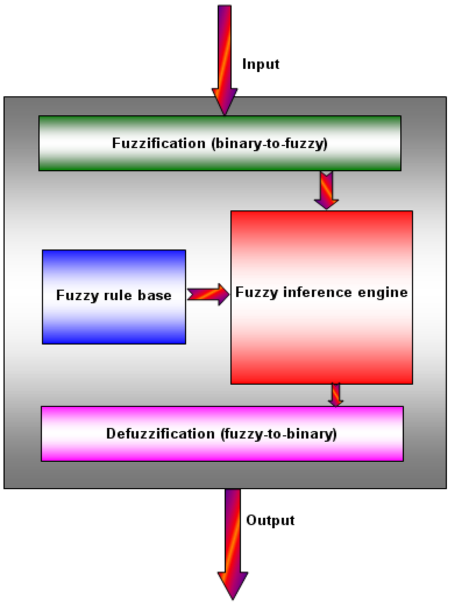


Figure 3. The structure of a fuzzy logic controller.

Fuzzy Logic controller executes the 49 control rules shown in Table 2 taking the fuzzy variables "e" and "de" as inputs and output quantity. The rules are formulated by using the knowledge of the PM synchronous motor behavior and the experience of control engineers.

3. COMPARATIVE SIMULATION AND EXPERIMENT RESULTS

The usage of simulation software packages for modeling, simulation, and optimization of control systems has become a part of regular engineering practice. Recently added features of such software packages like a possibility to generate real-time executable code directly from simulation models enabled shorter development times and faster validation of new control solutions. The solutions developed with the world standard software packages like Matlab, Matrix, or Mathematical, are available to a large number of users [1].

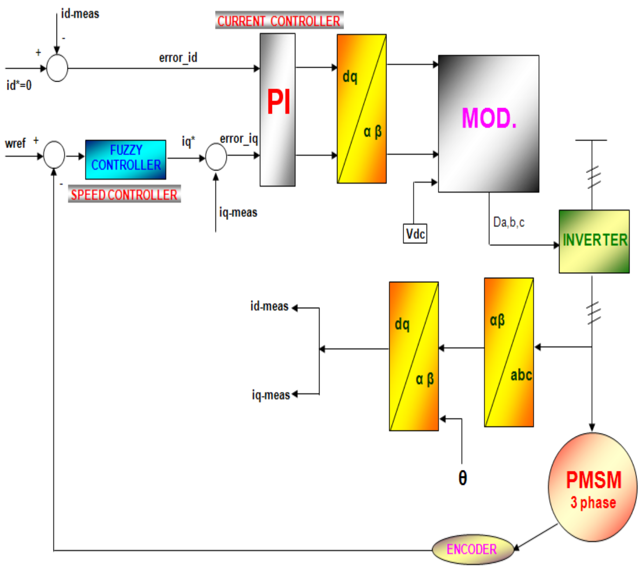


Figure 4. Control block of PMSM.

Since Matlab contains the Fuzzy Logic Toolbox (FLT) that allows the designer to create and test new fuzzy control designs, we give a short description of basic features of the Matlab Fuzzy Logic Toolbox needed for the successful usage of the tool.

For low speed operation of PM motors the flux weakening effect is not required, however the effect of flux weakening is deserved for the high speed operation of PMSM. Hence in this analysis, the direct axis reference current i_{dref} is considered to be zero for low speed operation. The d-q axis reference currents i_{dref} and i_{qref} are used to generate the reference currents i_{aref}, i_{bref} and i_{cref} in the reference current generator.

The reference currents have the shape of sinusoidal wave in phase with respective back emf to develop a constant and unidirectional torque. In PWM current regulating block, the motor winding currents are compared with the reference currents and the switching commands are generated for the inverter devices.

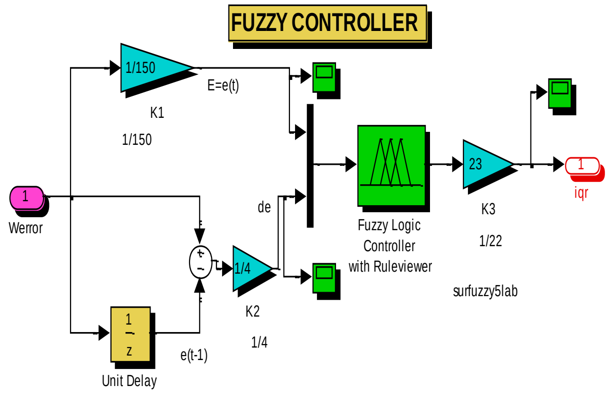


Figure 5. Fuzzy block for PMSM.

The goal of designed FLC in this study is to minimize speed error. The larger speed error the bigger controller input is expected. In addition, the change of error plays an important role in define controller input. Consequently FLC uses error *e(t)* and change of error *de(t)* for linguistic variables which are generated from the control rules. Equations determine required system equations. The output variable is the change in control variable *du(t)* of motor driver. Here K_1, K_2, and K_3 are each gain coefficients and t is a time index.

$$e(t) = [\omega_{ref}(t) - \omega(t)]K_1 \quad (5)$$

$$de(t) = [e(t) - e(t-1)]K_2 \quad (6)$$

$$du(t) = [u(t) - u(t-1)]K_3 \quad (7)$$

The error (e) approaches to its smallest value when the motor speed is attained to nominal value. If we reverse this value, the error interval can be defined between -60 and 60. In order to optimize the speed control, the intervals of membership functions are found after some manual changes as follow:

e_w: -150 and +150 rad/s
de_w: -4 and +4 rad/s/s
u: 23 and -23

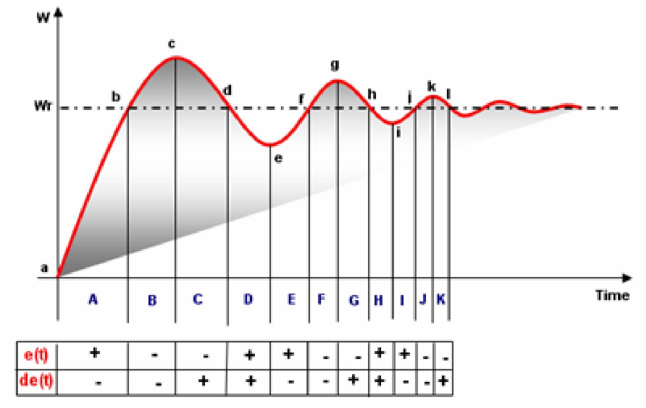


Figure 6. Output for rule table.

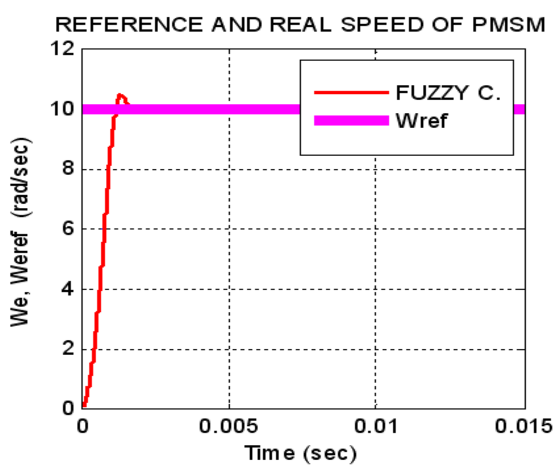
The gain values are determined for these intervals in simulation model as K_{1e}=1/150, K_{2de}=1/4 and K_{3u}=23.

System speed comes to reference value by means of the defined rules. For example, first rule on Table II determines, 'If (e(t) is NB) and (de(t) is NB) then (u(t) is NB)'. According to this rule, if error value is negative big and change of error value is negative big than output will negative big.

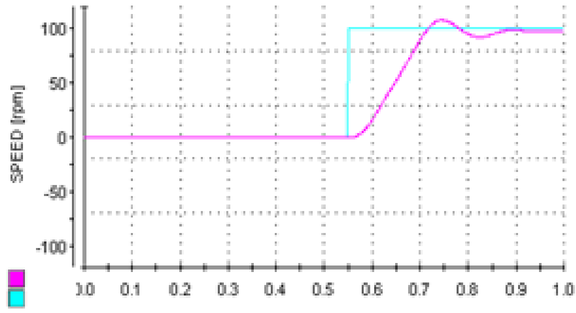
Table 2. Rule Table For Fuzzy Controller.

de(t) / e(t)	NB	NM	NS	ZERO	PS	PM	PB
NB	NB	NB	NB	NM	NS	PM	PS
NM	NB	NB	NB	NB	NM	NM	PB
NS	NB	NB	NM	NS	PS	PS	PM
ZERO	NB	NM	NS	ZERO	PS	PM	PB
PS	NM	NS	NS	PS	PM	PM	PB
PM	NS	NM	PS	PM	PB	PB	PB
PB	NB	PS	PM	PB	PB	PB	PB

The user can decide to these rules with their experiment. For example, B interval in Figure 6, motor speed is larger than reference speed and still wants an increase strongly. This state corresponds to decrease motor voltage decreasing. All conditions in the control process are shown in Figure 6.



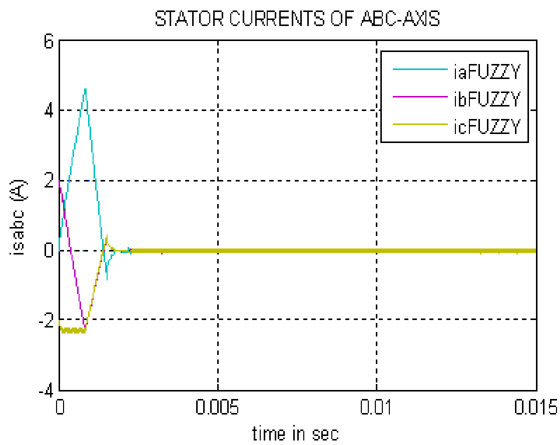
(a)



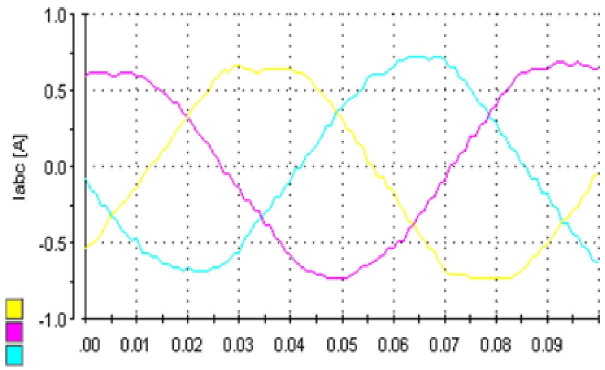
(b)

Figure 7. a) Simulation results, **b)** Experimental results for speed.

Figure 7 shows the motor starting response in which it takes around 0.0015 seconds for fuzzy to reach the set reference speed. This figure shows simulation results of Fuzzy controller and experiment results for Fuzzy controller.



(a)

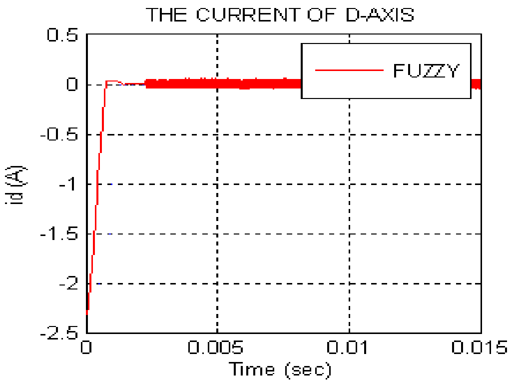


(b)

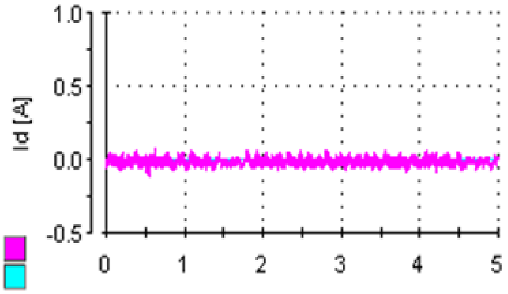
Figure 8. a) Simulation results, **b)** Experimental results for i_{abc}.

DSpace program what is used for connection from computer to motor in real system. 25 rules are used at fuzzy in real system for controlling because the data communication of fuzzy in Matlab is faster than DSpace.

ISSN: 2651-5199



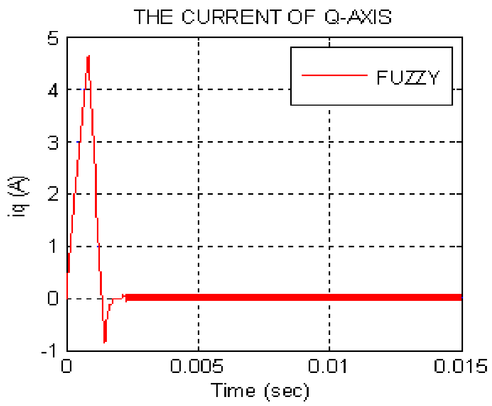
(a)



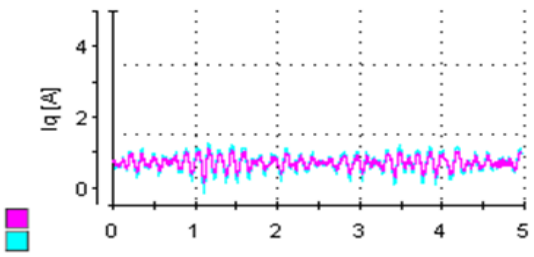
(b)

Figure 9. a) Simulation results, **b)** Experimental results for i_d.

The speed reaches to reference speed very fast by fuzzy. The overshoot can be regulated by Fuzzy. Figure 8 shows stator currents of abc-axis of PMSM.



(a)



(b)

Figure 10. a) Simulation results, **b)** Experimental results for i_q.

Figure 9 shows flux linkage of d-axis of PMSM. The figure shows that i_d current is zero. It means that experimental works are true. Figure 10 shows flux linkage of q-axis of PMSM. This current is changed by torque.

4. CONCLUSION

PMSM speed control has been performed in Matlab Simulink environment. PMSM speed has been controlled with Fuzzy Logic Controller (FLC). In this study, it is also designed a circuit model as a driver to get more reasonable results. This paper shows that simulation of Fuzzy Logic Controller has clearly better performance for providing T_r (rising time), e_{ss} (steady state error) and t_r^* (rising time to reference speed) $\%M_p$ (percent overshoot) criteria in comparison to the experimental results. FLC also has more sensitive responses against load disturbances in according to classical PID controller.

Table 3. Experimental And Simulation Results For Fuzzy Controller.

	Simulation Results	Experimental Results	Discrepancy	Signal
t_r (s)	0.00125	0.08	0.07875	(-)
e_{ss} (s)	0.0015	0.3	0.2985	(-)
M_p (%)	3	3	0	(+)
t_r^* (s)	0.0013	0.1	0.0987	(+)

The fuzzy controller can be used at sensitive applications. PMSM has been used widely in the control system of high performance depending development of the power electronic and control technology. However, the performances of the PMSM are very sensitive to the parameter and load variations.

Finally the fuzzy controller generates the variations of the reference current vector of the PMSM speed control based on the speed error and its change. The fuzzy controller is better then classical control because this control method can be regarded as an adaptive control based on a linguistic process. The linguistic process is however is based on prior experience and heuristic rules used by human operators.

ACKNOWLEDGEMENTS

The authors would like to thank Associate Professor Ewen RITCHIE, Aalborg University in Denmark for his contributions of knowledge and good ideas to this project and also would like to thank Lu KAIYUAN and Gaizka ALMANDOZ for their help at laboratory in Denmark too.

REFERENCES

[1] C.-F. J. Kuo, C.-H. Hsu, C.-C. Tsai, Control of a Permanent Magnet Synchronous Motor With a Fuzzy Sliding-Mode Controller, *Springer-Verlag London Limited 2006, DOI 10.1007/s00170-005-0393-2.*

[2] M.K. Rahmat, S. Jovanovic, K.L. Lo, Reliability and Availability Modelling of Uninterruptible Power Supply Systems Using Monte-Carlo Simulation, *International Review of Electrical Engineering (IREE), vol. 1 n. 3*, August 2006, pp. 374 – 380.

[3] J.R. Hendershot, T.J. Miller, *Design of Brushless Permanent-Magnet Motors*, (UK, 1994).

[4] Harris, J., *Fuzzy Logic Applications in Engineering Science*, National University of Science and Technology, Zimbabwe, (Springer, ISBN-13 978-1-4020-4078-8).

İstanbul
GEDİK
University
2651-5199