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ORIGINAL ARTICLE

FPGA-based self-organizing fuzzy controller for electromagnetic filter

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Abstract Electromagnetic filters (EMF) are used to clean magnetic particles in industrial liquids which play important roles to sustain the high-quality material production in industrial fields. In this study, an FPGA-based adaptive fuzzy controller is realized to sustain high performance of an EMF. An experiment is performed by using realized adaptive controller on an EMF set. The results obtained from the experiment are compared with the results of the conventional fuzzy controller. It is observed that adaptive fuzzy controller is performed better than the conventional fuzzy controller.

Keywords Adaptive control · Fuzzy control · Magnetic filter control · Magnetic separation

1 Introduction

One of the most important and common problems in many industrial area is to sustain the production of high-quality materials in manufacturing process. An important factor is that industrial liquids used in technological treatments do not maintain their chemical and physical properties during production processes [1]. Many of the included mixtures of the industrial liquids contain particles with magnetic properties [2, 3]. Mentioned magnetic particles should be cleaned up from technological liquids to sustain the quality processes. The use of electromagnetic filters (EMF) is preferred for cleaning the technological fluids from these particles with magnetic properties, because of their many advantages such as ability to operate at temperatures as high as Curie temperature, ability to not distort the chemical properties of the technological fluid and their high performance [1, 4, 5].

EMF filter matrix elements consist of materials having ferromagnetic properties. Filter matrix elements are magnetized by an external homogeneous field and create high gradient field areas around themselves [6–8].

Particles having magnetic properties inside the industrial liquid passing through the filter matrix pores are held in the active regions by the effect of powerful external magnetic field (Fig. 1). The particle-capturing capacity of the EMFs highly affects their performances [1, 8–10].

Electromagnetic filter performance (EMFP) depends on many parameters like length of the filter matrix, size and shape of the matrix elements, flow rate of the liquid to be cleaned, external magnetic field intensity[1, 8, 11]. Keeping the EMFP in high value presents an importance in filtering the industrial liquid which is an important factor increasing the quality of the produced materials. EMFs' performance change graph versus time is given in Fig. 2.

It can be seen from Fig. 2 that EMFP is in high value in Region I, but starts decreasing in Region II. This means that output particle concentration of the EMF increases. Consequently, it means that particles cannot be held in capturing regions anymore. In Region III, particle-capturing capacity of pores is exceeded and output particle concentration is eventually grown to match the input particle concentration. For this reason, to sustain the EMFP in Region II, there are many magnetic flux control studies are present [8, 9, 11, 12]. In the literature, fuzzy controllers are used to control the EMF's external magnetic field intensity with the parameters of input particle concentration in

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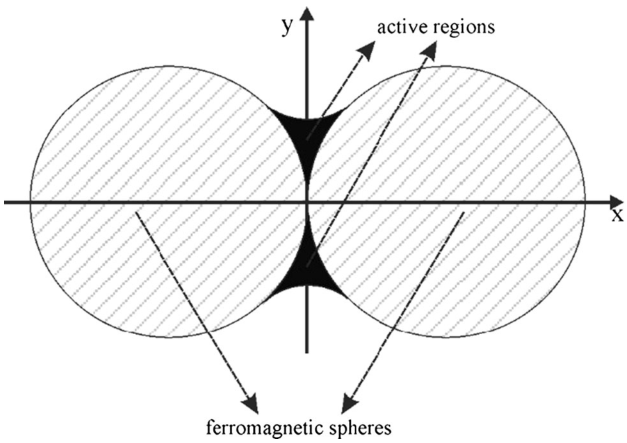


Fig. 1 Cutaway view of capturing region among the filter matrix elements

industrial liquid and liquid flow rate and applied controller is performed better than constant flux density controller in Region II (Fig. 3) [8, 9].

In this study, fuzzy controller given in the literature [12] is aimed to adapt itself to the change in EMFP and the consequent change in factors affecting the performance. For this purpose, a fuzzy adaptation system which adjusts parameters of fuzzy controller according to EMFP change is realized and applied to EMF system. Also, the effects of the realized adaptive control on the energy consumption were examined.

2 EMF experiment set

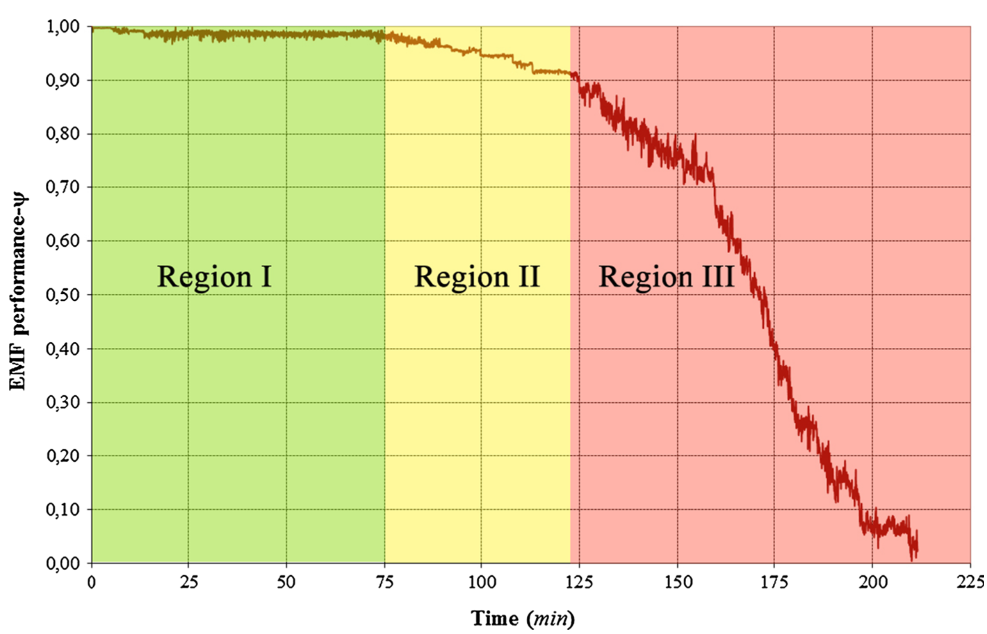
In this study, EMF set of Selcuk University, Engineering Faculty Magnetic Filtration Laboratory, is used (Fig. 4). Detailed properties and working principles of the EMF set are given in the study "The Control of Magnetic Filters by FPGA based Fuzzy Controller" [10].

Filter matrix in EMF set is formed by using 14-mm-diameter balls having magnetic properties as mentioned in the literature [8]. In this used EMF set, input particle concentration (IPC), output particle concentration (OPC) and liquid flow rate (FR) are measured by sensors and transferred to FPGA by means of an ADC. Incoming data are evaluated by the FPGA control program, and EMF magnetic flux change is provided by a DAC [10, 11]. Additionally, the data can be transferred from FPGA and stored in a computer by using RS232 transfer protocol.

3 Self-organizing fuzzy logic controller

Fuzzy control methods are very good alternatives for conventional control methods for the cases where it is hard to acquire detailed model and general working principles [13–16]. Parameters of the fuzzy control are designed according to opinion and knowledge of an expert. In many situations, because of lesser online adaptability fuzzy controllers cannot guarantee system performance [17]. One of the developed fuzzy control strategies against unforeseen changes in the system, noise and corruptive effects is self-organizing fuzzy control (SOFC). This control structure has learning algorithm in addition to classical fuzzy control structure. Control parameters can be changed by an adaptation signal without any knowledge about system dynamics [14, 17]. SOFC is chosen for EMF control because of not needing a mathematical model and because of its ability to adapt itself to changing parameters with time.

Fig. 2 EMF performance change [8]



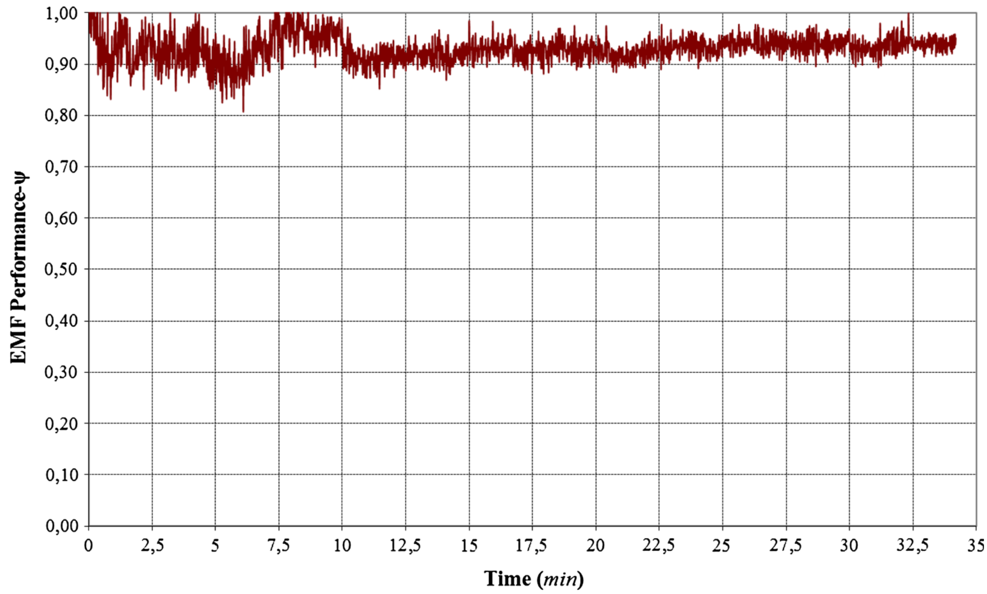


Fig. 3 Fuzzy-controlled EMF performance change [8]

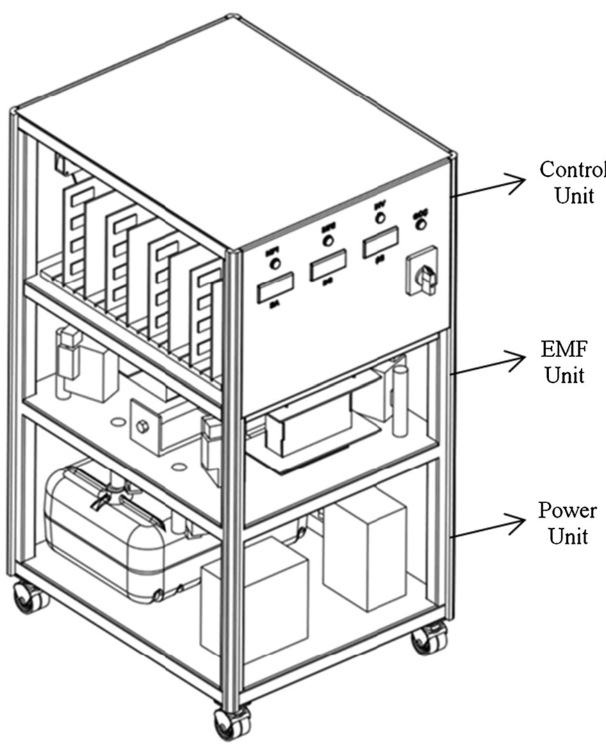


Fig. 4 EMF set

Designed SOFC controller has two layers as seen in Fig. 5. The first layer is fuzzy controller layer formed by the rules determined by experts. Adaptive fuzzy controller of the second layer adjusts the output membership function centers of the first-layer fuzzy controller [14, 18]. The first-layer fuzzy controller has a structure of two inputs and one output. In this structure, IPC and FR are input parameters and PWM reference voltage which provides magnetic flux change is output parameter.

In the first layer, input values are converted into linguistic expressions by using triangular membership function given in Figs. 6 and 7 by a Mamdani fuzzifier. In the figures, triangular memberships are defined as very very low (VVL), very low (VL), low (L), medium (M), high (H), very high (VH) and very very high (VVH).

Fuzzy controller rule in the first layer is given in below structure (Eq. 1).

$$R = \text{If } S_1 \text{ is } F_i \text{ and } S_3 \text{ is } F_j \text{ then } u \text{ is } U_{n(i,j)} \tag{1}$$

Here S_1 is input particle concentration, S_3 is flow rate, u is control signal, F_i is linguistic expression of S_1, F_j is linguistic expression of S_3, $U_{n(i,j)}$ is linguistic variable of u. Mamdani minimum implication and centroid defuzzifier are used to calculate control signal u (Eq. 2).

$$u = \frac{\sum_{i,j}\left[\left(\mu_{F_i}(s_1) \cap \mu_{F_j}(s_3)\right) \cdot U_{n(i,j)}\right]}{\sum_{i,j}\left(\mu_{F_i}(s_1) \cap \mu_{F_j}(s_3)\right)} \tag{2}$$

EMFP is calculated according to IPC and OPC in calculation module (Eq. 3).

$$\%\text{EMFP} = \left(1 - \frac{\text{OPC}}{\text{IPC}}\right) \times 100 \tag{3}$$

SOFC located in the second layer has inputs with error $e(k)$ which is difference of the EMFP from desired performance (EMFP_{ref}) (Eq. 4) and $\Delta e(k)$ is change in error at time instant k (Eq. 5).

$$e(k) = \text{EMFP}_{\text{ref}} - \text{EMFP} \tag{4}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{5}$$

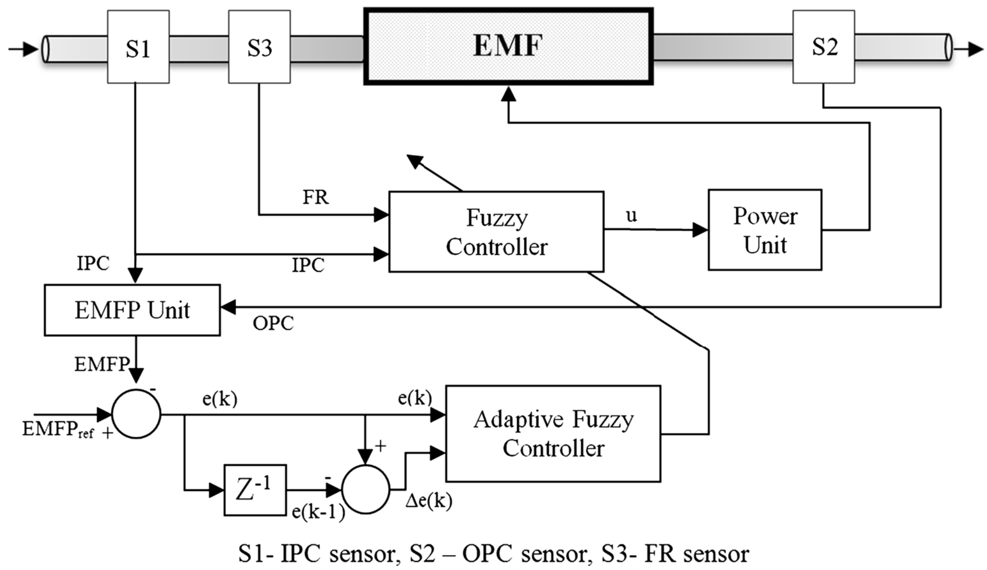


Fig. 5 Block diagram of designed control system

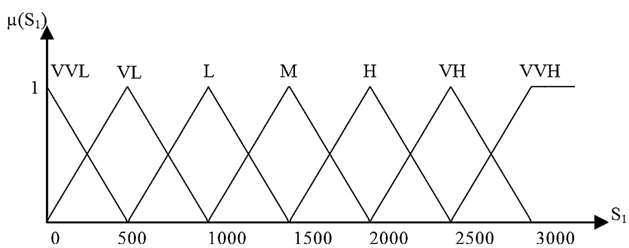


Fig. 6 Input particle concentration membership function

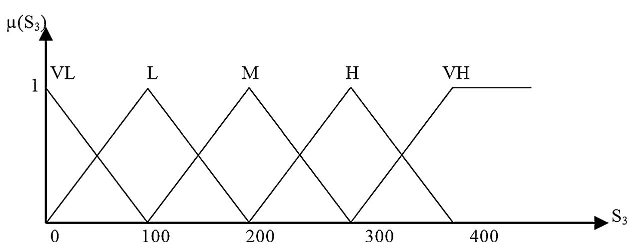


Fig. 7 Flow rate membership function

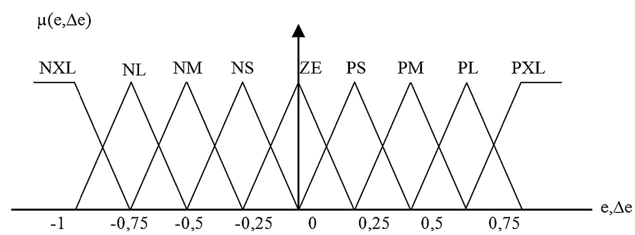


Fig. 8 Error and error change membership functions

Table 1 Fuzzy rule table for the first layer

S_3	S_1						
	VVL	VL	L	M	H	VH	VVL
VL	100	350	700	1050	1400	1750	2100
L	350	700	1050	1400	1750	2100	2450
M	700	1050	1400	1750	2100	2450	2800
H	1050	1400	1750	2100	2450	2800	3150
VH	1400	1750	2100	2450	2800	3150	3500

In the second layer, input values are converted into linguistic expressions by using triangular membership function given in Fig. 8 by a Mamdani fuzzifier. In Fig. 8, triangular memberships are defined as negative extra-large (NXL), negative large (NL), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), positive large (PL) and positive extra-large (PXL).

SOFC rule in the second layer is given in below structure (Eq. 6).

$$R = \text{If } e_1 \text{ is } E_k \text{ and } e_2 \text{ is } E_l \text{ then } c \text{ is } C_{m(k,l)} \tag{6}$$

Here e_1 is error $e(k)$ at time instant k, e_2 is change of the error $\Delta e(k)$, c is SOFC output which provides change in center of fuzzy controller output membership function. E_k is linguistic expression of e_1, E_l is linguistic expression of e_2, and $C_{m(k,l)}$ is linguistic variable of c.

SOFC in the second layer is used to compensate the unexpected noise and time-varying parameters in the system. The output membership function $U_{n(i,j)}$ of the first-layer fuzzy controller is tuned by the second-layer SOFC. Using Mamdani minimum implication and centroid

Table 2 Fuzzy rules table for the second layer

e	Δe −1	−0.75	−0.5	−0.25	0	0.25	0.5	0.75	1
−1	1	1	1	1	0.75	0	0	0	0
−0.75	1	1	1	0.75	0.5	0	0	0	0
−0.5	1	1	0.75	0. 5	0.25	0	0	0	0
−0.25	1	0.75	0. 5	0.25	0	0	0	0	0
0	0.75	0.5	0.25	0	0	0	−0.25	−0.5	−0.75
0.25	0	0	0	0	0	−0.25	−0.5	−0.75	−1
0.5	0	0	0	0	−0.25	−0.5	−0.75	−1	−1
0.75	0	0	0	0	−0.5	−0.75	−1	−1	−1
1	0	0	0	0	−0.75	−1	−1	−1	−1

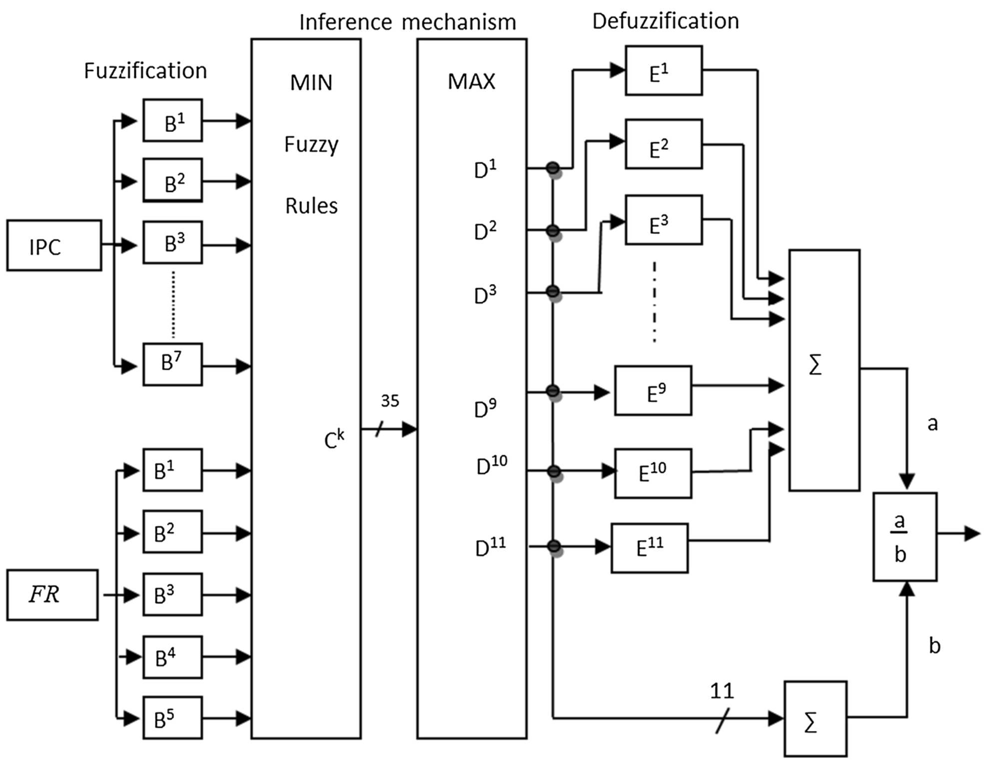


Fig. 9 Fuzzy logic controller block diagram

defuzzifier, output membership function of the first-layer fuzzy controller is updated with Eq. 7 as can be seen in [14].

$$U_{n(i,j)} = U_{n(i,j)} + \frac{\sum_{i,j}\left[\left(\mu_{E_k}(e_1) \cap \mu_{E_l}(e_2)\right) \cdot C_{m(k,l)}\right]}{\sum_{i,j}\left(\mu_{E_k}(e_1) \cap \mu_{e_l}(e_2)\right)} \quad (7)$$

The increase in the values of FR and IPC, which are the inputs of the first layer, has a reducing effect on EMFP [10]. For EMF control, the first-layer fuzzy rule table prepared according to this information is given in Table 1.

As it is seen form Table 1, to keep EMFP at a high level, PWM reference voltage, which enables the change of magnetic flux due to the rising FR and IPC values, has to be increased.

The second-layer SOFC fuzzy rule table, which tunes the output membership functions of the first-layer fuzzy controller in accordance with EMFP, is given in Table 2.

When Table 2 is examined, it can be seen that the upper-right and bottom-left values are zero, which means an adjustment is not necessary on the first-layer fuzzy controller. For example, error values at the bottom-left part of the table are positive, but the error values are decreasing gradually, which means there is a trend toward the desired EMFP level. For this reason, the values at the bottom-left part of the table are kept as zero. On the other hand, it can

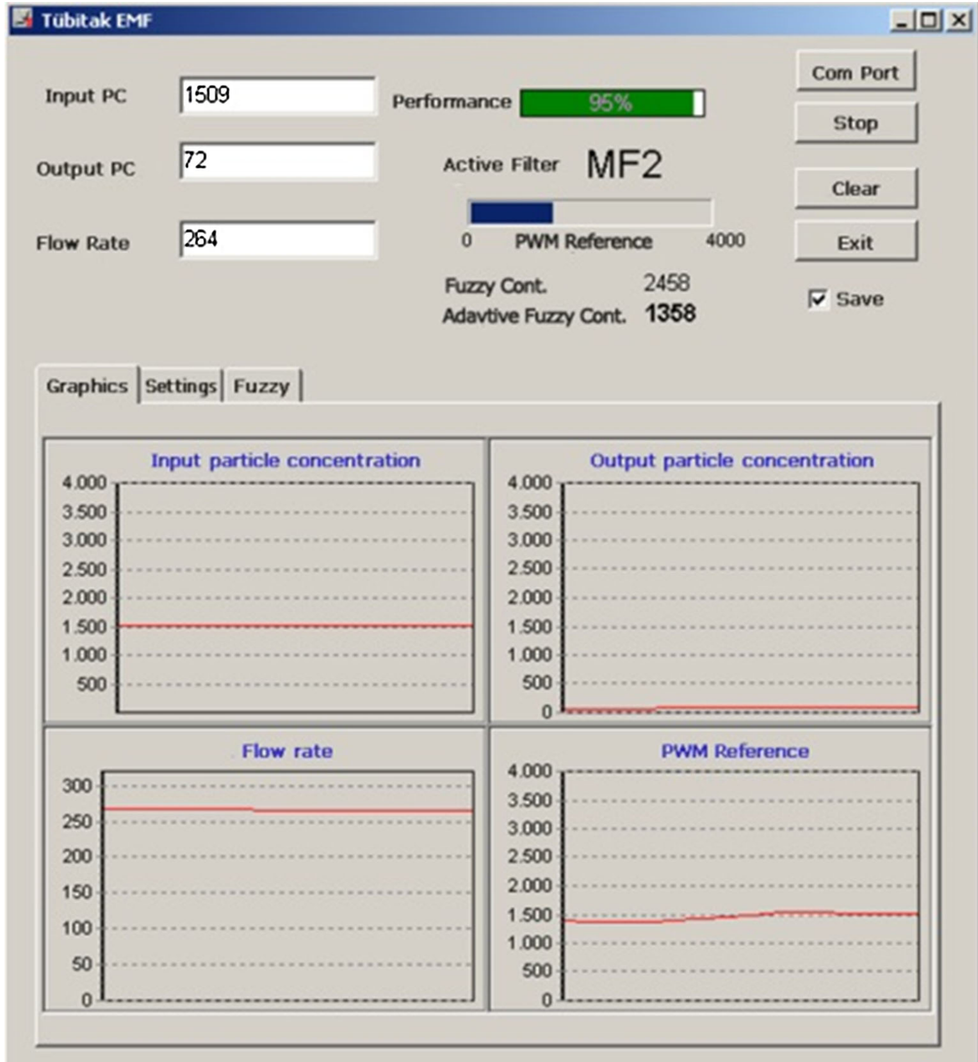


Fig. 10 EMF software interface

be seen that the first-layer output membership functions are tuned for the upper-left and bottom-right parts, where the error value gradually increases.

4 FPGA-based SOFC

SOFC structure given in Fig. 5 is programmed by using VHDL language in FPGA. SOFC coded in Altera Quartus program is synthesized by using 66176 elements of 68416 logic elements of Cyclone II EPC70F896 FPGA. Fuzzy controllers in SOFC are designed as components. Fixed point number notation consisting of 12 bits of integer part and 7 bits of fraction part is used to represent the control data [19]. General block diagram of fuzzy control realized on FPGA is given in Fig. 9. Results are determined after the fuzzification of fuzzy control inputs, inference mechanism and defuzzification listed, respectively, as seen in Fig. 9.

5 Control experiment

Industrial liquid used in the experiment is prepared as a suspension in a reservoir by using 200 liters of purified water by adding iron powder of 4–10 × 10–4 mm size. During the experiment, IPC, OPC, FR, magnetic flux applied to EMF and the first-layer membership function changes are transferred via RS232 interface to a computer. To store the experimental results and follow the system changes in the computer, software is created by using Delphi 8 (Fig. 10).

Experiment is realized in the EMF's Region II (Fig. 2) working conditions. During the experiment, FR is changed

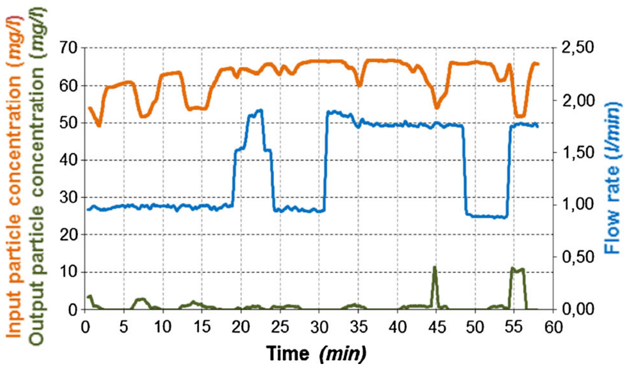


Fig. 11 IPC, OPC and FR in SOFC

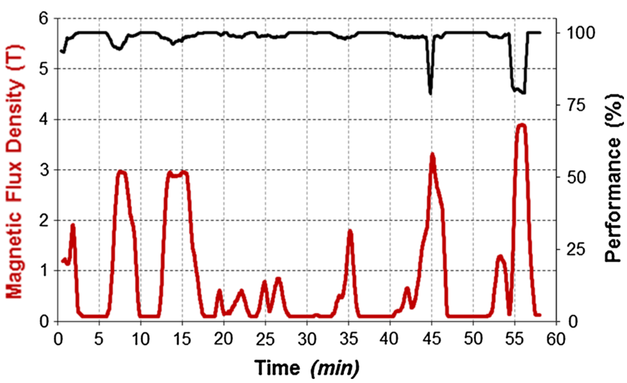


Fig. 12 EMFP and magnetic flux density in SOFC

by using a pump. IPC is changed either adding water or iron powder of 4–10 $\times$ 10^{-4} mm size into the reservoir. $EMFP_{ref}$ is defined as 99 %, and experiment is completed in 35 min.

During the experiment, changes of IPC, FR and OPC are determined as seen in Fig. 11.

6 Results and proposals

Magnetic flux change and EMFP of the experiment realized by using SOFC are determined as seen in Fig. 12.

When the EMFP decreases, SOFC adjusts the magnetic flux density by changing center of the first-layer output membership functions (Fig. 12). Thus system adapts itself according to changes in performance in Region II.

In performed experiments, magnetic flux density changes depending on IPC and FR by using only the first-layer fuzzy controller without using adaptation layer are determined as seen in Figs. 13 and 14.

When Figs. 13 and 14 are examined, it can be seen that the first-layer fuzzy control without adaptive processing changes magnetic flux density according to IPC and FR. In

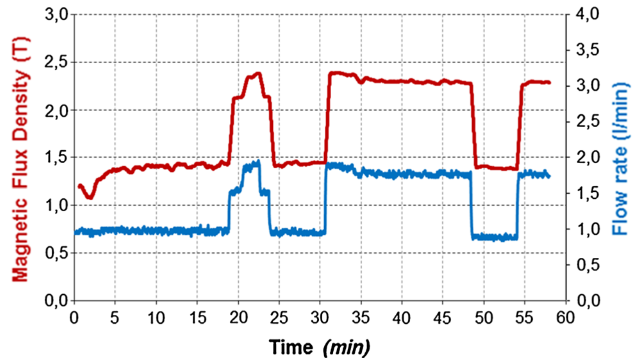


Fig. 13 Magnetic flux density and FR for the first-layer fuzzy controller

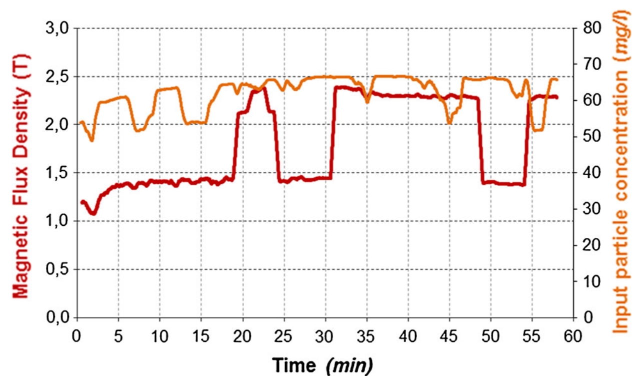


Fig. 14 Magnetic flux density and IPC in the first-layer fuzzy controller

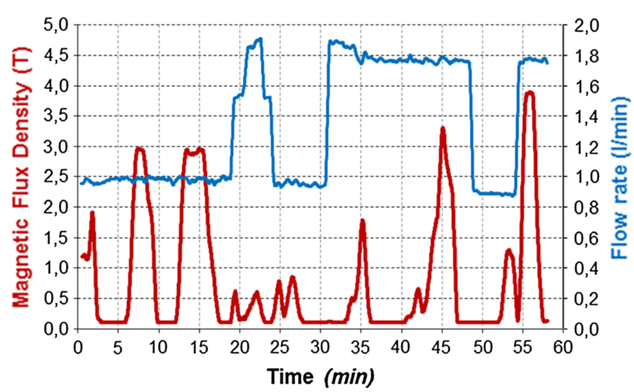


Fig. 15 Flow rate and magnetic flux density in SOFC

addition, when the first-layer magnetic flux density is compared to performance changes, it can be observed that in the cases of performance reduces, there is no change in the first-layer controller. On the other hand, for SOFC, it can easily be seen that magnetic flux density changes as the EMFP changes (Fig. 12).

While SOFC changes magnetic flux density in proportion to performance, magnetic flux density changes are also

Table 3 Energy consumption for the uncontrolled working of EMF and conventional fuzzy control cases

Conventional fuzzy-controlled filtration					Uncontrolled filtration				
U (V)	*I* (A)	*P* (kW)	Energy consumption		*U* (V)	*I* (A)	*P* (kW)	Energy consumption	
			kWh/day	kWh/year				kWh/day	kWh/year
2.6100	2.0100	5.2461	0.2098	76.5931	5.8000	4.4600	25.8680	1.0347	377.6728

Table 4 Energy consumption for the uncontrolled working of EMF and SOFC cases

SOFC filtration					Uncontrolled filtration				
U (V)	*I* (A)	*P* (kW)	Energy consumption		*U* (V)	*I* (A)	*P* (kW)	Energy consumption	
			kWh/day	kWh/year				kWh/day	kWh/year
1.1600	0.8900	1.0324	0.0413	15.0730	5.8000	4.4600	25.8680	1.0347	377.6728

observed where there are significant FR changes because of the first-layer FR outcome effects (Fig. 15). For example, between 18 and 22 min, FR value increases from 1 to 1.8 l/min, magnetic flux density increased from 0.1 to 0.6 T even if the performance value remains as 99.4 % constant. Thus SOFC control structure is able to respond to performance decrease resulting from sudden flow rate changes as noted in the literature.

To observe experimentally, suspension is used a higher concentration used in the industrial field. This particle density may cause uncontrollable particle accumulation or particle breaking-offs in the experiment set. In Fig. 11, the rise occurring in OPC between 44 and 45 min is thought to be because the particles detached from the portions between the input sensor and filter matrix.

Conventional fuzzy logic rules should be constructed by an expert depending on the parameters like dimension of micron-sized particles having magnetic properties in the industrial liquid, diameters of filter matrix and elements of filter matrix, length of filter matrix, magnetic permeability of filter body, viscosity of industrial liquid. Experiment results show that SOFC delivers more effective and suitable control to sustain the high EMFP since SOFC can adapt itself, especially in the Region II performance changes compared to conventional fuzzy control.

In the experiments of the EMF, maximum current and maximum voltage values should be used for uncontrolled case to obtain the same power as in the SOFC. Equation 8 is used for these calculations [9].

$$P = \frac{U \times I}{1000} \tag{8}$$

In Eq. 8, P power (kW), U average value of coil voltage (V), and I average value of coil current (A).

Daily energy consumption of the MF and annual energy consumption are calculated by using Eqs. 9 and 10, respectively [9].

$$W_g = P \times t_g \tag{9}$$

$$W_y = W_g \times t_y \tag{10}$$

W_g daily energy consumption (kWh), W_y annual energy consumption (kWh), t_g daily working duration of the MF (h), t_y annual working duration of the MF (days).

Energy consumptions of conventional fuzzy control filtration and uncontrolled filtration are calculated by using Eqs. 8–10. The calculated results are given in Table 3.

As it is seen from Table 3, conventional fuzzy-controlled filtration provides energy-saving rate of 79.71 % compared to uncontrolled filtration.

Energy consumptions of SOFC filtration and uncontrolled filtration are calculated by using Eqs. 8–10. The calculation results are given in Table 4.

As it is seen from Table 4, SOFC filtration provides energy-saving rate of 96.00 % compared to uncontrolled filtration.

The obtained results clearly show that because SOFC determines magnetic flux density according to EMFP, it delivers higher performance with lower magnetic flux densities compared to conventional fuzzy control. Consequently, it provides more energy savings compared to conventional fuzzy control.

Realized SOFC system can become more sensitive control system by increasing the fuzzy control rules. Additionally, more effective control systems can be developed by utilizing the system with powerful and higher process capacity FPGA and application of different artificial intelligence methods on hybrid structures.

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