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THEORETICAL AND EMPIRICAL IMPROVEMENT OF A FAST-SWITCHING ELECTRO-PNEUMATIC VALVE BY USING DIFFERENT METHODS

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Abstract: In this paper, a non-linear model of a 2–2 way, on–off fast-switching valve is used. The model includes subsystems of electrical, magnetic, mechanical and fluid. Pulse width modulation (PWM) technique is adopted to energise the on–off solenoid valve and allow the air to flow towards the actuator. Since the non-linear behaviour of valve is of great importance, to reduce the delay in performance of switching valves, different approaches are proposed. Furthermore, hysteresis, proportional integrator (PI), optimal model predictive and fuzzy logic controller (FLC) are used and compared. Also, to improve the valve behaviour, an empirical setup based on AVR microcontroller with FLC is implemented. Empirical and simulation results indicate that all proposed control methods have superior performance. However, the fuzzy method is easy to implement in practice.

Key words: on–off valve, electro-pneumatic, PWM, empirical, AVR microcontroller

1. INTRODUCTION

Since pneumatic control systems are of low cost, easy to maintain and cheap, they are used in industrial automation systems [1,2]. However, pneumatic actuators are highly non-linear, which results from air friction and the delayed time during air compression. Hence, electro-pneumatic actuators are preferred to the pneumatic actuators. There are two major types of electro-pneumatic valves that are used for conducting air, including on–off and servo valves [3]. Servo valve offers high precision and linear behaviour, but it has a complex and also expensive structure. Fast-switching on–off valve has a cost-effective and simple structure with intrinsically non-linear behaviour [1,4]. Pulse width modulation (PWM) method is adopted to attain a linear behaviour by using fast-switching valves.

For decreasing the complexity and costs of the systems, an on–off valve, which is driven by PWM signal, is used instead of servo valve [5]. By using the PWM approach, the valve is opened and closed periodically, so the air is allowed to flow towards the actuator to control the signal [6,7]. Many studies have utilised PWM signal for control applications, but a very early application uses PWM approach to control the fluid system [8]. Furthermore, Noritsu employed PWM approach for controlling the position and velocity of pneumatic piston [9,10]. Muto [11] used differential PWM approach for controlling hydraulic actuators.

Many researchers have conducted studies on modelling and control of electro-pneumatic actuators by using on–off fast-switching valve [12-15], but these studies have scarcely focused on on–off fast solenoid valve. In [16], a dynamic non-linear model of a 3-2 on–off valve is presented. The valve performance in terms of opening and closing was improved by using the proper control approach [17]. Wang et al.[18] modified a ferromagnetic material (Al–Fe) to have a strong magnetic force to achieve fast response. Other investigations into the characteristics of fast-switching on–off valves are given in [19,20].

There are different approaches for controlling electro-pneumatic systems [21-24]. Since the non-linear behaviour of the valve leads to delay in the performance, to compensate this defect, theoretical and practical controlling of valve behaviour has major importance, but this point has been rarely studied by researchers. Also, the number of valves opening and closing affect the lifetime of the on–off valves. Therefore, reducing the valve frequency and switching time delay have a great importance. Hence, in this paper, different control methods including hysteresis, proportional integrator (PI), optimal controller based on predictive approach and fuzzy logic controller (FLC) are proposed to improve the non-linear behaviour of valve. Also, in order to verify the theoretical results, an empirical setup including alf and vegards risc (AVR) microcontroller based on FLC is designed. It should be mentioned that in many industries, Programmable logic controllers (PLCs) are employed for controlling electro-pneumatic systems. Because PLC is not a cost-effective method, in the empirical setup, an electronic circuit based on AVR microcontroller is used.

The remaining of the paper is as follows: In section 2, a non-linear model of a 2–2 way valve is presented. Then, evaluation of the solenoid valve model is shown. Section 3 is dedicated to

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controller design for valve with PWM technique. The designs of hysteresis approach, PI controller, optimal controller based on predictive approach and FLC are also presented. In the next section, an empirical setup is presented to express the effectiveness of controllers. The conclusion is explained in the last section.

2. MODELLING OF AN ELECTRO-PNEUMATIC ON–OFF FAST-SWITCHING VALVE

As shown in Fig. 1, in this paper, for simulating the dynamic behaviour of valve equipped with designed control systems, the model of valve including four subsystems consisting of electrical, magnetic, mechanical and fluid is employed. More detailed information about the model is available in [2].

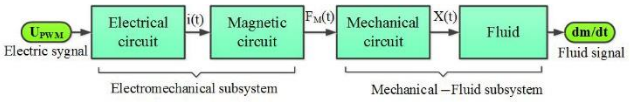

Fig. 1. Valve model components' subsystems

Now, for validation of the obtained model, the periodic input with duty cycle 50% is applied to the valve (Fig. 2). Results show the duration when the voltage input is applied; position behaviour is trivially analogous to dc input till the input is set to zero. As a result, both current and the position fall. The delay in position response originates from the practical model of the valve. Position reduction continues until the plunger goes backwards to the path beginning. Hence, it is observed that the modelled valve follows the input successfully.

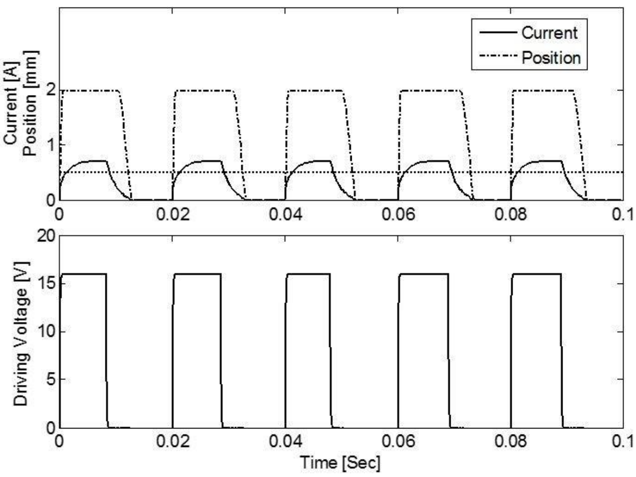

Fig. 2. Evaluation of the solenoid valve

3. DESIGN OF DIFFERENT CONTROLLERS FOR IMPROVING THE VALVE BEHAVIOUR

The valve is proposed to follow the performance as [16]; since the input voltage is applied to the coil at $t = 0$ sec, the current rises exponentially as long as the current reaches the desired amount, and then, due to the magnetic force applied to the spring force, the plunger of valve starts sliding. Since the system has a delay, the plunger of valve takes a certain time to fully open. The coil needs current, which is called holding current, to keep the valve fully open. Also, for opening the valve, the current required is called switching current. In practice, the holding current is less than the switching current [16]. In order to prevent the current from increasing after opening the valve and keeping it as holding current, several controllers are proposed and compared in the following sections. Also, for closing the valve, an electrical current should be fetched from the coil. Therefore, for reducing the time delay to close the on–off valve, using a first-order low-pass filter, a negative voltage can be applied into the coil as follows:

$$H(s) = \frac{1}{\tau s+1} \tag{1}$$

3.1. Hysteresis controller

In this section, in order to prevent the current from increasing after opening the valve, the hysteresis controller is designed in which the output is changed when the input exceeds its bound. In this controller, the signal is saturated as follows [2]:

$$\begin{cases} 1 & \text{if} \quad i_a \le i_d + \frac{H}{2} \\ 0 & \text{if} \quad i_a \ge i_d - \frac{H}{2} \\ \text{no change} & \text{if} \quad |i_a| < \frac{H}{2} \end{cases} \tag{2}$$

in which i_d and i_a are the desired and measured current, respectively, and G and H denote the output signal and the hysteresis bounds of the coil, respectively.

As seen in Fig. 3, this controller holds the current in a desired value; but due to the fluctuating nature of this method, the hysteresis controller has inevitable shortcoming and it reduces the lifetime of the valve.

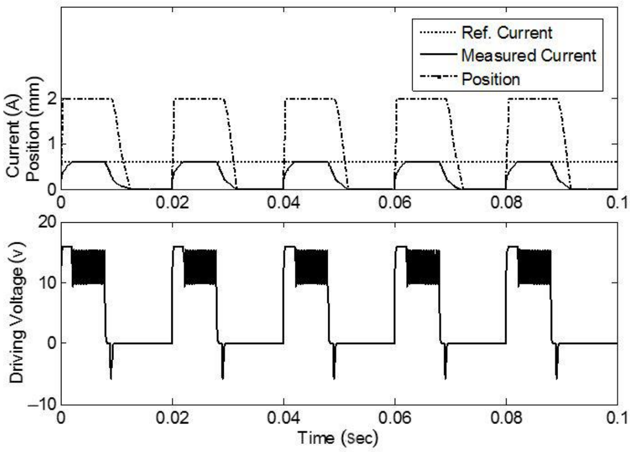

Fig. 3. Response of hysteresis controller

3.2. PI controller

As mentioned before, since the hysteresis controller has a fluctuating nature and it reduces the lifetime of valve, in this section, in order to enhance the valve behaviour during opening and closing, the PI controller, which is common in pneumatic control systems, is designed [16]. As seen in Fig. 4, this controller holds the coil current to the desired value after the valve is fully opened. In comparison with hysteresis controller, this controller holds the current of coil without frequent fluctuations, which is an important advantage of this controller.

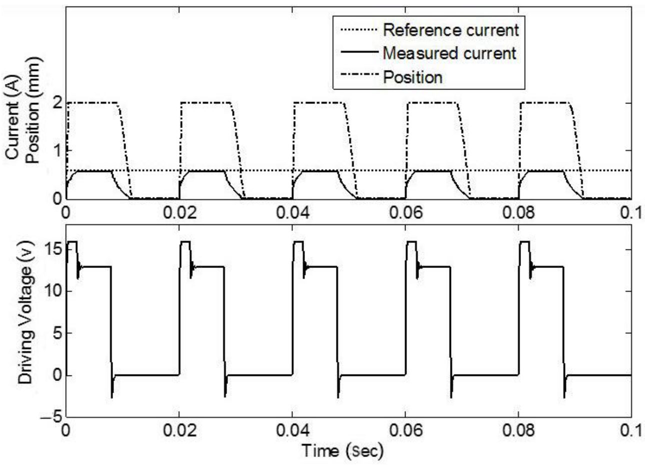

Fig. 4. Response of PI controller

3.3. Nonlinear optimal controller based on predictive approach

In this section, a model predictive-based controller is optimally designed. A 2- degree of freedom (DOF) model containing the main dynamics of solenoid is employed to calculate the voltage. The state variables of this model include the main and auxiliary ring current (I_1 and I_2). The governing equations are expressed as

$$\dot{I}_1 = c_e \left[\frac{V_1 - RI_1}{N_1} + \frac{R_2 B I_2}{D N_2}\right] \quad (3)$$

$$\dot{I}_2 = \frac{V_1 - RI_1}{N_1 B} - \frac{A c_e}{B}\left[\frac{V_1 - RI_1}{N_1} + \frac{R_2 B I_2}{D N_2}\right] \quad (4)$$

V_1 is the driving voltage of solenoid. The state space form of Eqs (3) and (4) is rewritten as

$$\dot{x}_1 = g_1 + \frac{1}{c_e N_1} V_1 \quad (5)$$

$$\dot{x}_2 = g_2 + \frac{1 - A c_e}{B N_1} V_1 \quad (6)$$

in which $X = [x_1\ x_2]T = [I_1\ I_2]T$ and V_1 are the state vector and the control signal, respectively. According to this method, a point-wise cost function that minimises the current control expenditure and the next current tracking error is defined as follows:

$$J = \frac{1}{2}\ w_I\ [I_1 - I_d]^2\ + \frac{1}{2}\ w_v V_1^2 \quad (7)$$

where, h is the prediction period and I_d is the referenced or desired response of current. Also, $w_I > 0$ and $w_v \geq 0$ are the weighting factors of current and control input, respectively. The Taylor series expansion at time t is used to expand the term $I_1(t + h)$ in Eq. (7) as follows:

$$I_1(\mathrm{t+h}) = I_1(\mathrm{t}) + h\dot{I}_1(\mathrm{t}) + \frac{h^2}{2!}\ddot{I}_1(\mathrm{t}) + \cdots + \frac{h^n}{n!}\ I_1^{(n)}(\mathrm{t}) \quad (8)$$

To prevent complexity in deriving and implementing the controller, the order of expansion in Taylor series is restricted to be equal with the relative degree of current in the non-linear system [31,32].

This selection, which is related to zero control order, removes the derivatives of the control input for predicting the control variables, which ends up in proper performance for nonlinear system with a small relative degree. Referring to Eqs (5) and (6), the relative degree of current is $\rho_1 = 1$, and therefore, the first-order Taylor series is enough to expand the current:

$$I_1(\mathrm{t+h}) = I_1(\mathrm{t}) + h\dot{I}_1(\mathrm{t}) = I_1(\mathrm{t}) + h\left[g_1 + \frac{1}{c_e N_1} V_1\right] \quad (9)$$

Substituting Eq. (9) into the cost function in Eq. (7) gives

$$J = \frac{1}{2} w_I\ \left[e_I + h\left(g_1 + \frac{1}{c_e N_1} V_1\right)\right]^2 + \frac{1}{2}\ w_v V_1^2 \quad (10)$$

where, $e_I(t) = I(t) - I_d$ is the current tracking error. The reference or desired response of current, I_d, is constant.

By minimising the cost function in Eq. (10) with respect to the current control input, the optimal control law for V_1 is achievable. The necessary optimisation condition is applied as follows:

$$\frac{\partial J}{\partial V_1} = 0\ \rightarrow\ V_1 = \frac{-c_e N_1}{h^2 + \frac{w_v c_e^2 N_1^2}{w_I\ h^2}}\ [e + h g_1] \quad (11)$$

The following theorem is given to prove the stability of the proposed integrated controller (Eq. (11)):

Theorem 1. The current dynamics in the presence of uncertainties is stable in the sense of Lyapunov under the control law in Eq. (11) with non-zero weights. Also, there exists a small predictive time h, so that the error converges to a compact set.

Proof 1. The current error dynamics in the closed-loop system is obtained by inserting the control law in Eq. (11) in the model of Eq. (5) as

$$\dot{I}_1 = g_1 - \frac{k}{h}\ [e_I + h\hat{g}_1] \quad (12)$$

where

$$K = \frac{h}{h^2 + \frac{w_v c_e^2 N_1^2}{w_I\ h^2}} \quad (13)$$

The symbol (ˆ) indicates the nominal model used for the controller design. Eq.(12) is rewritten to derive the error dynamics as

$$\dot{e}_I + \frac{k}{h} e_I = (g_1 - \hat{g}_1) + (1 - k)\hat{g}_1 \quad (14)$$

Deviation of g_1 from $\hat{g}_1$ may be due to model uncertainties and other errors in measurement or estimation. The function $\hat{g}_1$, including the internal current, is bounded. Therefore, the positive constants $\Gamma_1 > 0$ and $\Gamma_2 > 0$ exist, so that

$$|g_1 - \hat{g}_1| \leq \Gamma_1 \qquad |\hat{g}_1| \leq \Gamma_2 \quad (15)$$

The error dynamic in Eq. (14) is rewritten by using the bounds of Eq. (15) as

$$\dot{e}_I + \frac{k}{h} e_I \leq \Gamma_1 + (1 - k)\Gamma_2 \quad (16)$$

The Lyapunov candidate can be written as follows:

$$V = \frac{1}{2} e_I^2 \quad (17)$$

Substituting Eq. (14) into the derivative of Eq. (17) gives

$$\dot{V} \leq -\frac{k}{h} e_I^2 + [\Gamma_1 + (1 - k)\Gamma_2]|e_I| \quad (18)$$

Utilising the inequality $ab \leq ma2 + b2/4m$ for any real a, b and $m > 0$ gives the following:

$$\dot{V} \leq -\frac{k}{h} e_I^2 + \frac{k}{4h} + \frac{1}{k}[\Gamma_1 + (1 - k)\Gamma_2]^2 \leq -\frac{3k}{4h} V + \frac{k}{h}[\Gamma_1 + (1 - k)\Gamma_2]^2 \quad (19)$$

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where $m = \kappa/4h$. The inequality in Eq. (19) is solved by using the comparison lemma [31] as follows:

$$V = \frac{1}{2}e_I^2 \leq \left[V(0) - \frac{2h^2}{3k^2}[\Gamma_1 + (1-k)\Gamma_2]^2\right] e_I^{-\frac{3k}{2h}t} + \frac{2h^2}{3k^2}[\Gamma_1 + (1-k)\Gamma_2]^2 \quad (20)$$

It is clear that the current tracking error converges to the compact set $|e_I| \leq \frac{2}{\sqrt{3}}[\Gamma_1 + (1-k)\Gamma_2]\frac{h}{k}$. So, it is uniformly bounded for all times. For any given ε > 0, it can be chosen $0 < h < \frac{\sqrt{3}\varepsilon}{2[\Gamma_1+(1-k)\Gamma_2]}$ in the control law, Therefore, e_I converges to $|e_I| \leq \varepsilon$. So that, the stability of the control law in the sense of Lyapunov is proved.

Simulation results of using optimal model predictive control are shown in Fig. 5. As seen in this figure, the coil current tracks the desired value appropriately. In comparison with hysteresis controller, this controller holds the current of coil without frequent fluctuations, which is an important advantage of this controller. Also, the proposed controller which uses the continuous dynamic model is analytically calculated in the closed form and does not need online optimisation in calculation of the control input. However, the optimal model predictive controller is fast and easy to solve and implement in real times.

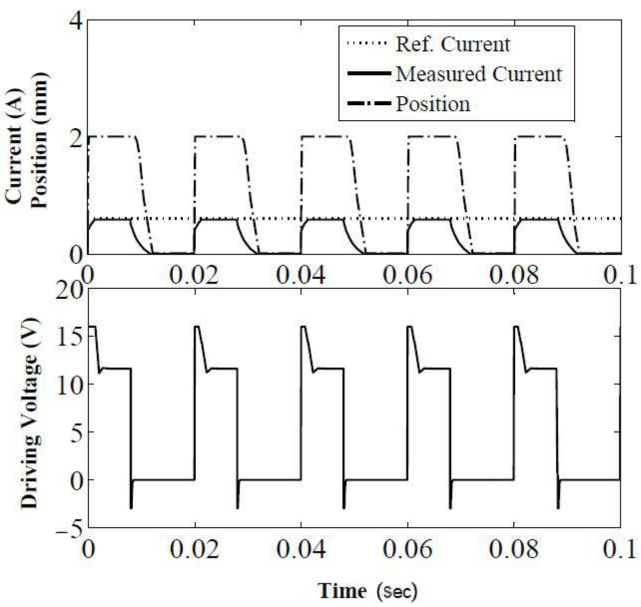

Fig. 5. Response of optimal model predictive controller

3.4. Fuzzy logic controller

In this section, the FLC is used for controlling the system current with negligible time delay. It should be mentioned that in empirical design, FLC is preferred over other controllers. In the first step of designing FLC, rules are designed for the current error and the rate of current error to get FLC response for a desired set point of bobbin current and keep it constant.

Fig. 3 shows the block diagram of FLC. In this figure, the stretched fuzzy controller provides variable voltage signal for control of bobbin current. As seen in Fig. 3, the feedforward structure is employed to compensate the measured disturbances before they have any effect on the system output. In the bobbin fuzzy control system, the current gain (Cg) is combined with an FLC to stabilise the bobbin current by tracking the input efficiently without considering external errors.

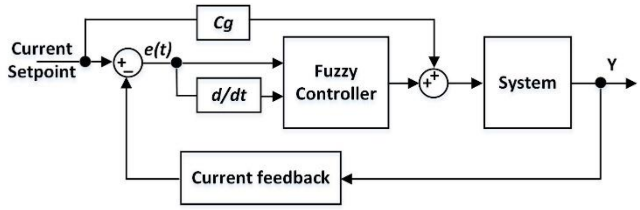

Fig. 6. Block diagram of FLC

In this paper, the FLC is designed based on Mamdani type [2]. As seen in Table 1, in the FLC, linguistic variables and rules are designed for the error and the rate of error to get an FLC response for the desired set point of the bobbin current. For instance, when the bobbin current moves down, the voltage of the bobbin increases gradually and the error decreases; on the other hand, when the bobbin current moves up, bobbin voltage decreases too.

Tab. 1. FLC rules

Error rate	Error				
	NL	NM	ZE	PM	PL
NL	VL	L	L	M	M
NM	L	L	M	S	S
ZE	L	M	S	S	VS
PM	M	M	VS	VS	VS
PL	S	S	VS	VS	VS

The linguistic variables including NL, NM, ZE, PM and PL represent negative low, negative medium, zero, positive medium and positive large, respectively.

Fig. 7 shows the general structure of the fuzzy controller consisting of fuzzification (functions that convert an explicit input to a fuzzy input) and inteference unit which is based on fuzzy rules and defuzzification (functions that convert fuzzy output to explicit output).

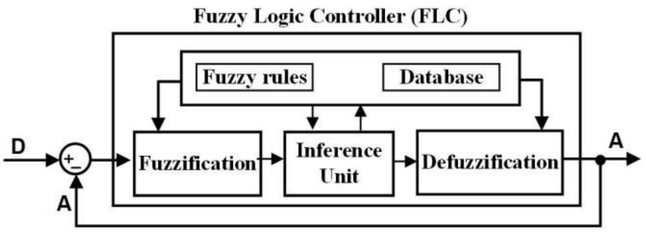

Fig. 7. General structure of FLC

FLC regulates the current by using the PWM signals in the bobbin driver. The error and the rate of error are the inputs of FLC. The error is determined as the difference between the measured and desired system current as:

$$E = A - D \quad (21)$$

where D and A are the desired and actual current, respectively.

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The FLC's membership functions are shown in Fig. 8. Also, the control surface is indicated in Fig. 9.

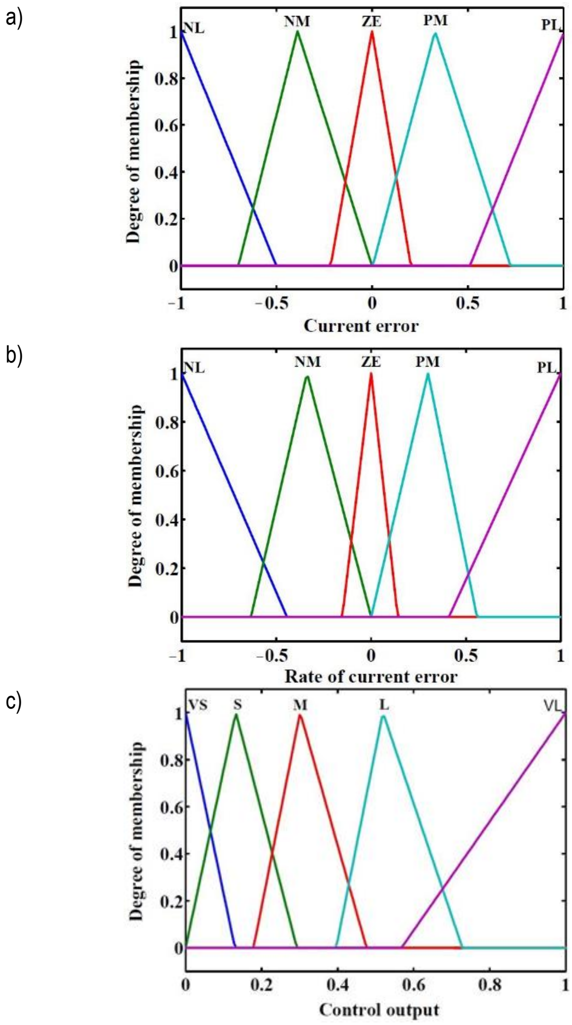

Fig. 8. Membership functions of FLC: (a) current error, (b) rate of current error, (c) control output

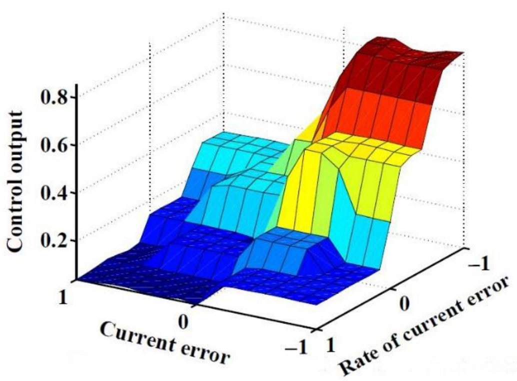

Fig. 9. Surface of FLC

Simulation results of using fuzzy control in order to track the desired current are presented in Fig. 10. As shown in this figure, the position and current verify the effectiveness of this controller. In comparison with hysteresis controller, this controller holds the current of coil without frequent fluctuations, which is an important advantage of this controller. Also, the fuzzy controller which needs no equations is easy for experimental implementation.

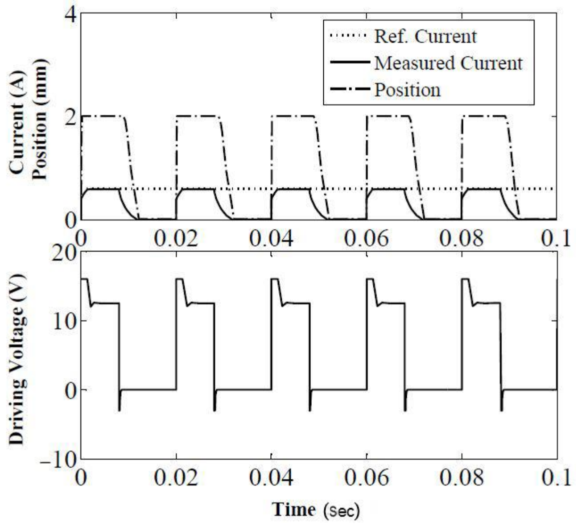

Fig. 10. Response of fuzzy controller

3.5. Comparison of designed controllers

In this section, evaluation of the controllers' performance is performed using controller effect and root mean square error (RMSE). Comparison of the dynamic performance of the four controllers is given in Table. 2. The obtained results show that the performance of FLC is better than that of the other three controllers. It should be mentioned that due to non-linearity of the system, the results of optimal controller based on predictive approach and FLC are better than the other two controllers and are approximately similar, but the fuzzy method is easy to implement in practice.

Tab. 2. Comparison of performance results for the designed controllers

Controller type	Controller effect	RMSE
Hysteresis	1.300247	0.095237
PI	1.250031	0.086718
Optimal model predictive	1.220253	0.080158
FLC	1.216844	0.079451

FLC, fuzzy logic controller; PI, proportional integrator

4. EMPIRICAL SETUP

In this section, an empirical setup consists of a solenoid, and a control circuit is implemented to enhance the performance of a solenoid valve. Fig. 11 shows an empirical setup of the system, which is controlled by using AVR microcontroller and FLC designed in the previous section. A solenoid of valve is a coil that pushes (or pulls) a plunger or spool until the current flows through it. There are several types of solenoids: push and pull types, with and without springs for pushing back the spool or plunger until the current no longer flows. Solenoids have some advantage in comparison with motors, including effecting a linear movement based on a compact mechanism without gears. On the other side, solenoids have a limited stroke.

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In this paper, a small pull-type solenoid is utilised, which has a spring for pushing the plunger or spool back out.

The coil's resistance is 3.6 ohms, which draws 3.33 A when it is connected to a 12 V supply.

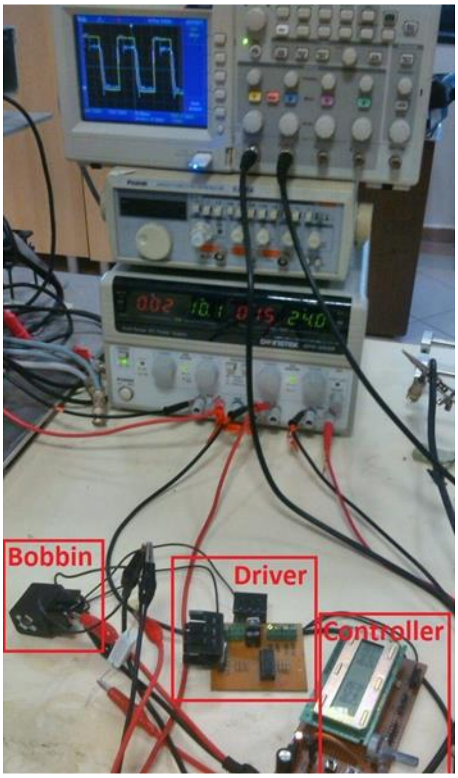

Fig. 11. The structure of empirical setup

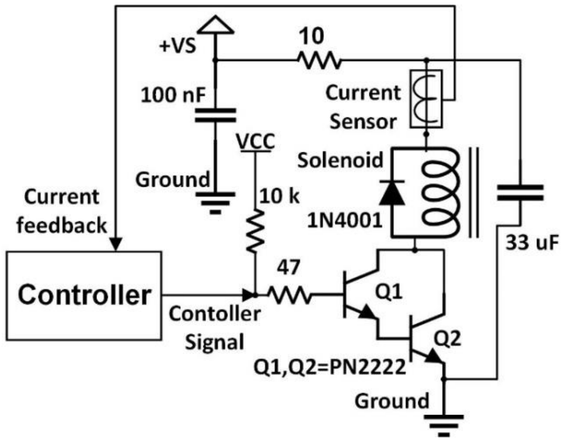

Fig. 12. The structure of control circuit

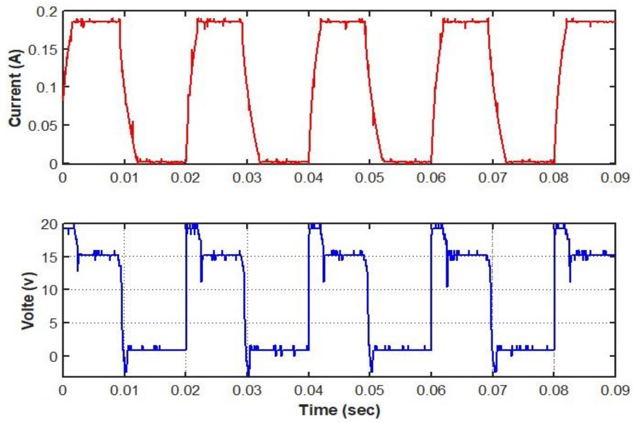

Fig. 13. Empirical performances: current and voltage

4.1. Driving the solenoid

Fig. 12 shows the structure of the control circuit. The solenoid is connected to one of the controller ports in series with two resistors, where each resistor is equal to 1 ohm, which is for the safety of the circuit. It should be mentioned that the total resistance is more than 6 ohms, which limits the current of port to less than 1.5 A.

The solenoid is activated using the PWM at the specified duty cycle. The port voltage and the solenoid's current are measured using an oscilloscope, which is shown in Fig. 13.

The controller increases the voltage of the coil immediately. Due to the inductance of the coil, the current ramps up. This causes the voltage of coil to drop from about 15 V to less than 12 V. Then, the current continues to remain constant.

When the controller reduces the voltage, the current ramps down gradually, which causes a short negative voltage spike when the protection diode in the system starts conducting. When the voltage across it drops to under the threshold of diode, the protection diode stops conducting and the low negative voltage lingers in the port for a while longer.

The capacitor connected to the solenoid coil is charged through a 10 resistor that gives a 0.33 msec RC constant. It should be mentioned that, the used capacitor has an adequate capacitance to store sufficient charge and also low adequate internal resistance in discharge process.

5. CONCLUSION

In this paper, the model of a fast-switching valve of 2–2 way, based on PWM, has been employed. To enhance the valve performance and decrease the delay in opening and closing, several controllers consisting of hysteresis, PI, optimal model predictive and fuzzy controllers are comparatively designed and implemented. Among the employed control approaches, PI, optimal model predictive and fuzzy controllers have faster performance, and it causes the valve to have long lifetime. Also, in comparison with other controllers, the FLC needs no equations and is easy to implement empirically.

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