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# The Speed and Torque Control of Direct Current Servo Motors by using Cascade Fuzzy PI Controller

***Abstract***. *Direct current servo motors (DCSMs) are frequently used in the areas of industry which require different operating conditions. Traditional PI controllers with constant coefficients are not sufficient for the speed and torque control of these motors, because of that their dynamic characteristics change in different operating conditions. The speed and load changes cause positive and negative overshoots and oscillations. In this study, in order to overcome these problems, the speed and torque controls of DCSM were implemented by using the cascade fuzzy PI controller, where the torque control was carried out by the current control. For this aim, a cascade fuzzy PI controller was designed for controlling the speed and the current of DCSM. Here, the fuzzy logic controllers in cascade fuzzy PI controllers adjusted the proportional and integral coefficients according to the speed and the change of speed, and the current and the change of current. The experimental results showed that the performance of cascade fuzzy PI controller was better than that of traditional PI controller for different operating speed and load conditions.*

***Streszczenie.*** *Opisano metodę sterowania serwomotorem o prądzie bezpośrednim DCSM przy wykorzystaniu kaskadowego kontrolera bazującego na logice rozmytej. Analizowane są: prędkość i zmiany prędkości oraz prąd i jego zmiany. Umożliwia to precyzyjną kontrolę momentu napędowego i prędkości serwomotoru. (**Sterowanie szybkością i momentem serwomotoru o prądzie bezpośrednim z wykorzystaniem kontrolera bazującego na logice rozmytej**)*

**Keywords:** Direct current servo motor, PI controller, Cascade fuzzy PI controller.
**Słowa kluczowe:** serwomotor, sterowanie napędem, logika rozmyta.

## I. Introduction

Direct current servo motors (DCSMs) are usually used as a first actuator in the control systems of computers, digitally controlled machines, industrial tools, weapon industry, and full-automatic regulators for a fast and accurate start. Although the characteristics of DCSMs like inertia, physical shape, cost, shaft resonance and shaft structure have similar values, their physical and electrical constants are variable [1]. The fact that they have low rotor inertia and therefore high moment values makes the servo motors indispensable in the control applications.

There are a lot of control methods for the servo motors. Traditional P, PI and PID controllers are usually used in various systems due to their simple structure, cheap costs, simple design and high performance [1]. For the nonlinear systems, the coefficients of P, PI and PID controllers are adjusted by either trial and error method or frequently by using methods such as Ziegler-Nichols, Åström-Hägglund, etc. However, the adjusted coefficients cannot provide high success in the DCSMs which have dynamic operating conditions, and also they are affected by the change of noise and system parameters [2-3].

In literature, there are many studies on the speed control of DCSM. Akar and Temiz prepared the simulation program of DCSM model in the Matlab and designed controllers for the speed control of DCSM based on PID, fuzzy logic control (FLC) and adaptive neuro-fuzzy inference system (ANFIS) [4]. Akar and Cankaya modeled DCSM in Labview program by designing a graphical user interface. They designed PI and PID controllers for the simulation model, and compared their results with the real time results [5]. Rigatos estimated the unknown values of the DCSM by using an artificial neural network, and designed a controller based on ANFIS [6]. In another study, Rigatos implemented to evaluate the performance of the Kalman filter and the Particle filter in reconstructing the state of the DCSM and subsequently in using this state estimation in feedback control [7]. Ananthababu and Amarendra measured the performance of the traditional PID and fuzzy PI controllers and observed that the fuzzy PI controller provided better results than the other in nonlinear operating conditions [8]. Algreer and Kuraz carried out the speed control of DCSM by using PID and fuzzy PID controllers in the simulation model, and concluded that the fuzzy PID controller was more successful [9]. Jinli et al. controlled the speed by using a fuzzy-PI control system for brushless direct current motor which has greater inertia load. They showed that the success of this controller system was higher than that of traditional PI controller [10].

The performances of P, PI and PID controllers used in electrical servo motor drives have been improved by means of artificial intelligent based controllers such as fuzzy logic and ANFIS, and in this way, providing robust speed control [9-13 ].

In this paper, we proposed a novel cascade fuzzy PI controller to dynamically control the speed and torque of DCSM in order to improve the performance of the drive system and overcome the overshoots occurring during the changes of speed and load for nonlinear operating conditions.

The remaining of the paper is organized as follows: Section 2 describes the mathematical model of the DCSMs. Sections 3 and 4 explain the control method and the application, respectively. Experimental results are analyzed in Section 5. Finally, the paper concludes with Section 6.

## II. Mathematical model of Direct Current Servo Motor

DCSMs is widely preferred for high performance systems requiring minimum torque ripple, rapid dynamic torque, speed responses, high efficiency and good inertia [1]. These motors speedily respond to a command signal by means of a suitable controller. In this kind of motors, the speed control is carried out by changing the supply voltage of the motor [14]. Development of a high performance controller to ensure reliable speed for systems is a topic of interest of many researchers. Fig. 1 shows the equivalent circuit of DCSM.

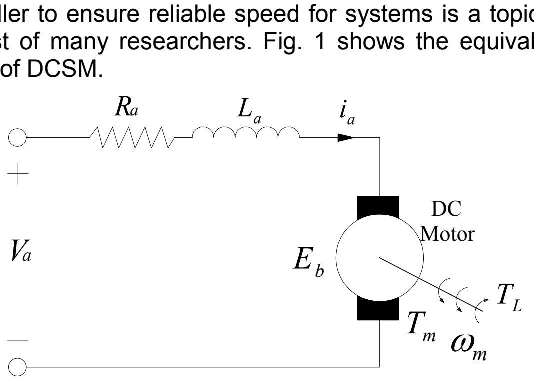


Fig.1. The equivalent circuit of DCSM

From the equivalent circuit in Fig. 1, the equations of DCSM can be described as

(1) $$V_a(t) = R_a . i_a(t) + L_a \frac{di_a(t)}{dt} + E_b(t)$$

(2) $$T_m = j\frac{d\varpi(t)}{dt} + B.\varpi(t) + T_L(t)$$

By applying the Laplace Transform to these equations when the initial conditions are taken as zero, the following equations are obtained.

(3) $$I_a(s) = \frac{V_a(s) - K\varpi(s)}{R_a + L_a s}$$

(4) $$s\varpi(s) = \frac{K}{j} I_a(s) - \frac{B}{j}\varpi(s) - \frac{T_L(s)}{j}$$

(5) $$\varpi(s) = \frac{KI_a(s) - T_L(s)}{B + sj}$$

(6) $$E_b(s) = K_b w(s)$$

(7) $$\frac{\omega(s)}{V_a(s)} = \frac{K}{s^2 J_m L_a + s J_m R_a + KK_b}$$

## III. Cascade Fuzzy PI Controller

The coefficients of PI controller should be continuously adjusted to the values within the predefined interval of the PI coefficients [15] since the traditional PI controllers do not provide optimal performance in the speed and torque controllers of the DCSM in dynamic operating conditions. FLCs dynamically adjust the coefficients of PI controller, and hence the cascade fuzzy PI controller with these adjusted coefficients performs the speed and torque controls of DCSM. Fig. 2 shows a block diagram of the speed and torque controls of DCSM implemented by using the cascade fuzzy PI controller.

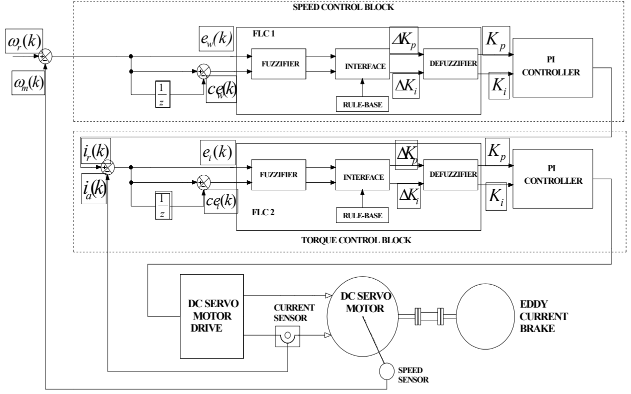


Fig. 2.Block diagram of the speed and torque controls of DCSM implemented by using cascade fuzzy PI controller

As seen in Fig. 2, the speed and torque controls of the motor are carried out by the speed and torque control blocks, respectively. FLC1 and FLC2 within these blocks have two different rule bases in order to adjust the proportional coefficient ($K_p$) and integral coefficient ($K_i$) for the speed and current. The values of $K_p$ and $K_i$, independently from each other, are reproduced in different operating conditions according to the current errors and change of these errors, and used as control signal in a following loop.

The speed error $e_w(k)$ and the speed error change $ce_w(k)$ for each sampling time in the speed control are given below:

(8) $$e_w(k) = \omega_r\ (k) - \omega_m(k)$$

(9) $$ce_w(k) = e_w(k) - e_w(k-1)$$

The current error $e_i(k)$ and the current error change $ce_i(k)$ for each sampling time in the torque control are described as

(10) $$e_i(k) = i_r(k) - i_a(k)$$

(11) $$ce_i(k) = e_i(k) - e_i(k-1)$$

Each *e* and *ce* input variable of FLCs designed for the speed and torque control has 7 membership functions. The linguistic definitions of their fuzzy sets are named [16] as Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Big (PB). Fig. 3 and 4 illustrate the input membership functions of FLCs used for the control of speed and torque, respectively.

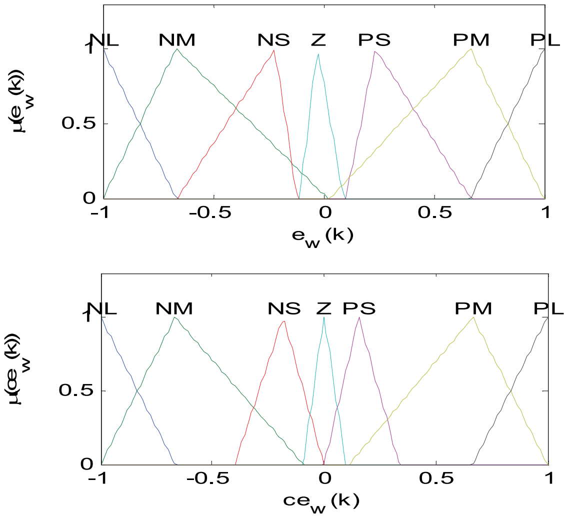


Fig. 3. FLC1 input membership function

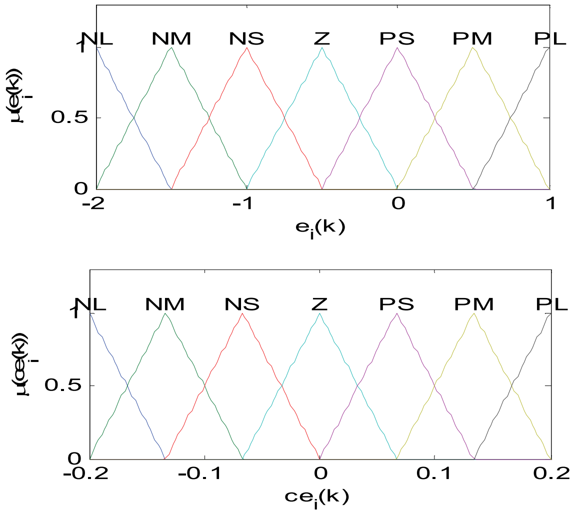


Fig. 4. The input membership functions of FLC2

At first, while the motor requires a higher Kp value during reaching to the reference speed value from stationary state, it must be have a smaller Ki value for no overshooting when reaching to the reference speed value. Also, while the motor operates at the reference speed, the value of Kp must be smaller than that of reaching the reference value and the value of Ki must be higher than that of reaching the reference value [2]. For this aim, the outputs of $K_p$ and $K_i$ were computed by using Ziegler Nichols method [2] in the range of [15, 18] and [30, 50] for FLC1, and [30, 50] and [0.5, 1.5] for FLC2, respectively. The designed FLC1 and

FLC2 controllers continuously adapt Kp and Ki coefficients for the current conditions. Each FLC has two outputs determining the optimum values of $K_p$ and $K_i$ coefficients of PI controllers. The linguistic definitions of output variables of FLCs are Small (S), Medium (M), and Large (L). Fig. 5 and 6 show the output membership functions of used FLCs.

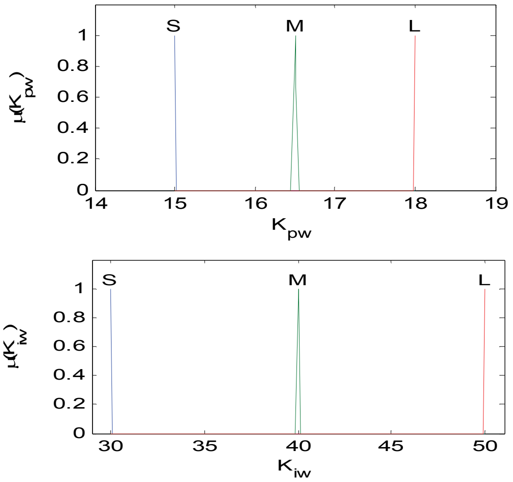


Fig. 5. The output membership functions of FLC1

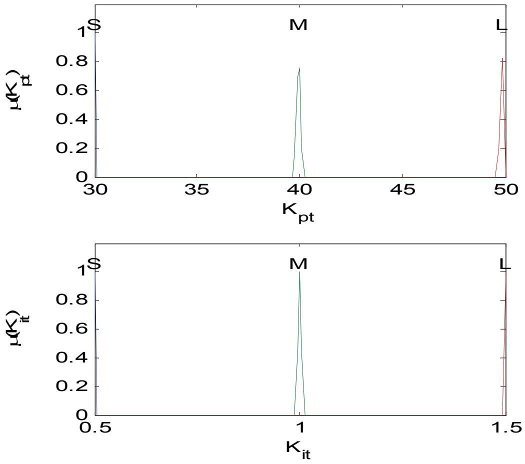


Fig. 6. The output membership functions of FLC2

The following rule structures are used in the fuzzy inference part of FLCs [18].

(12) If $e_w(k) = NM$ and $ce_w(k) = NS$ then $K_p = S$ and $K_i = L$

(13) If $e_i(k) = NM$ and $ce_i(k) = NS$ then $K_p = S$ and $K_i = L$

Defuzzification was carried out by the following Eq. 14 and 15 representing the centroid defuzzification method [19].

$$K_p = \frac{\sum_{i=1}^{n} (\Delta K_p)_i \, \mu[(\Delta K_p)_i]}{\sum_{i=1}^{n} \mu[(\Delta K_p)_i]} \tag{14}$$

$$K_i = \frac{\sum_{i=1}^{n} (\Delta K_i)_i \, \mu[(\Delta K_i)_i]}{\sum_{i=1}^{n} \mu[(\Delta K_i)_i]} \tag{15}$$

where, $\Delta K_i$ and $\Delta K_p$ represent the fuzzy inference results of the $K_i$ and $K_p$ while $\mu(\Delta K_i)$ and $\mu(\Delta K_p)$ refer to minimum membership values. Rules used for $K_p$ and $K_i$ in FLCs are given in Tables 1 and 2, respectively.

Table I. Rule table of *Kp* for speed and torque control

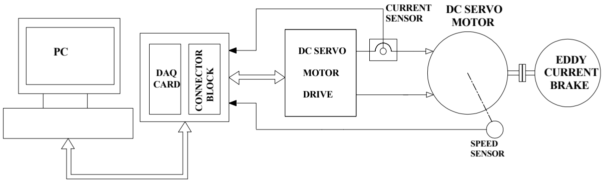
| $K_p$ | | *e(k)* | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | NL | NM | NS | Z | PS | PM | PL |
| *ce(k)* | NL | S | S | S | M | L | L | L |
| | NM | S | S | S | M | L | L | L |
| | NS | S | M | M | M | M | M | L |
| | Z | M | M | M | M | M | M | M |
| | PS | L | M | M | M | M | M | S |
| | PM | L | L | L | M | S | S | S |
| | PL | L | L | L | M | S | S | S |

Table II. Rule table of *Ki* for speed and torque control

| $K_i$ | | *e(k)* | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | NL | NM | NS | Z | PS | PM | PL |
| *ce(k)* | NL | L | L | L | M | S | S | S |
| | NM | L | L | L | M | S | S | S |
| | NS | L | L | M | M | M | S | S |
| | Z | M | M | M | M | M | M | M |
| | PS | S | S | M | M | M | L | L |
| | PM | S | S | S | M | L | L | L |
| | PL | S | S | S | M | L | L | L |

## IV. Application

In this paper, we set the experimental setup in Fig. 7 in order to implement the speed and torque controls of a DC servo motor. The real time application was implemented by using PCMCIA 6062 E DAQ board, CR Magnetic CR5410 AC field effect current transducer and WST-9 DC servo motor set. Parameters of used motors are given Table 3:



a) The block diagram of experimental setup

b) The experimental setup

Fig. 7. The experimental setup and its block diagram

Table III. The DCSM parameters

| Parameter | Symbol | Value and unit |
|---|---|---|
| Armature resistance | $R_a$ | 1 Ω |
| Armature inductance | $L_a$ | 0.9 m H |
| Armature current | $I_a$ | 3.44 A |
| Torque constant | $K$ | $6*10^{-2}$ Nm/A |
| Back EMF constant | $K_b$ | $6*10^{-3}$ V/rad/s |
| Moment of rotor inertia | $J_m$ | $0.223*10^{-4}$ kgm$^2$ |

## V. Experimental setup

In this paper, the speed and torque controls of DCSM were implemented in unloaded, full loaded and sudden loaded operating conditions. Unloaded and full loaded experiments were carried out for the reference speeds changing depending on time, and the range of references was divided into four separate zones: Zone 1, Zone 2, Zone 3 and Zone 4. Zone 1 and 4 continued for one second, the others continued for two seconds. Transitions to the reference speeds were carried out in ramp changes for the desired time intervals. For all operating conditions, the performances of PI and cascade fuzzy PI controllers were separately tested.

Fig. 8 shows the speed and torque responses of the PI controller for the unloaded operating conditions. PI controller provided a stable transition in Zone 1. In Zone 2 and 4, it followed the reference value. In the beginning of Zone 3, the reference value was caught during 0.411 seconds after a big oscillation.

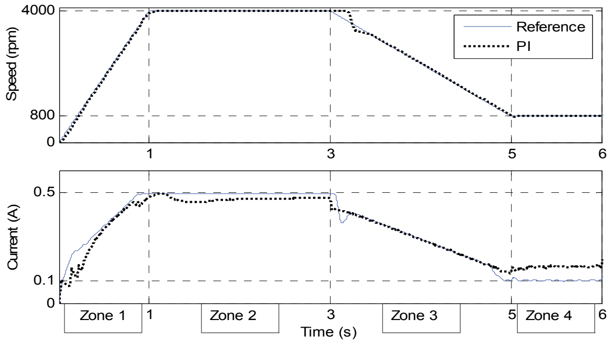


Fig. 8. The speed-time and current-time responses of PI controller in unloaded operating condition

In point of the torque control, as seen in Fig. 8, the current is below the reference value in the beginning, it has an oscillating change, and also it could not catch the reference. In Zone 2, the value of reference current was followed with 5% error. In zone 3, the reference value could be caught in 0.27 seconds after an oscillation in the beginning. In Zone 4, the reference was followed with approximately 50% error in the positive direction and the torque control couldn't be implemented at the desired level in this zone. The performance of the designed cascade fuzzy PI controller was tested for the same operating conditions. Fig. 9 shows the speed and torque responses of the cascade fuzzy PI controller for the unloaded operating conditions. As seen in Fig. 9 for Zone 1, 2, 3 and 4, the speed control performed by the cascade fuzzy PI controller was steadily implemented at the reference value.

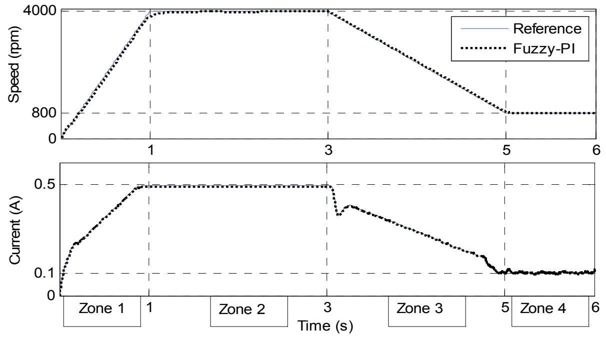


Fig. 9. The speed-time and current-time responses of cascade fuzzy PI controller in unloaded operating condition

In the transition to Zone 2 from Zone 1, the reference value was caught after the delay of 0.11 seconds. In the torque control of this controller in the unloaded operating condition, the reference current was followed in all zones and the aimed torque control was carried out without error. Fig. 10 illustrates the speed-time and the current-time responses of PI controller in the full loaded operating condition. As seen in Fig. 10, in the speed control of the PI controller of DCSM in the same load operating condition, Zone 1 was followed below the reference value of 2% and the reference value was caught after the delay of 0.07 seconds in Zone 2.

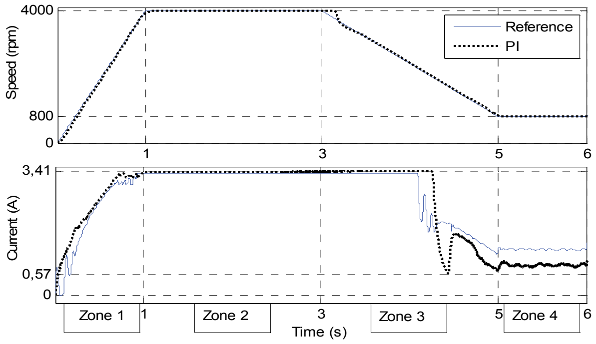


Fig. 10. The speed-time and current-time responses of PI controller in full loaded operating condition

The transition to Zone 3 from Zone 2 was carried out after the delay of 0.38 seconds, and the operating was performed in the reference value in Zone 4. In point of the current control, the reference value could only be followed in Zone 2, while it could not be caught in other zones. Fig. 11 illustrates the speed-time and current-time responses of cascade fuzzy PI controller in full loaded operating condition.

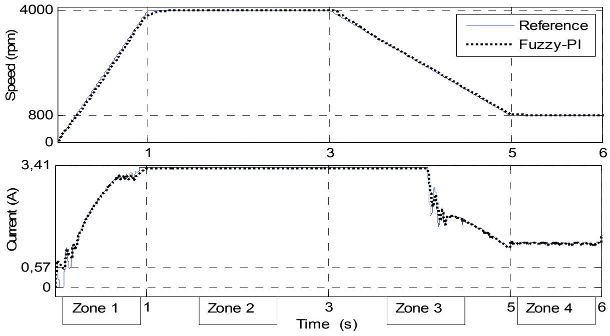


Fig. 11. The speed-time and current-time responses of cascade fuzzy PI controller in full loaded operating condition

As seen in Fig. 11 the reference speed value was followed within an acceptable tolerance interval of all zones, but there was only a delay of 0.08 seconds in the transition from Zone 1 to Zone 2. While the reference value in the torque control was caught in the beginning of the Zone 1 and Zone 3 after the oscillation, the desired control was performed in the other zones. As seen in Figure 10, after fourth second, the current response to the drive could not follow the reference current. However, as seen in Figure 11, the offered method was significantly successful within this range. The responses of the designed controllers for the sudden load change were tested. The obtained results were illustrated in Fig. 12 and 13.

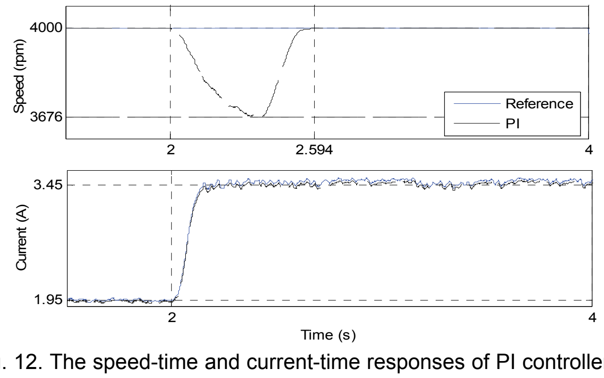


Fig. 12. The speed-time and current-time responses of PI controller in sudden loaded operating condition

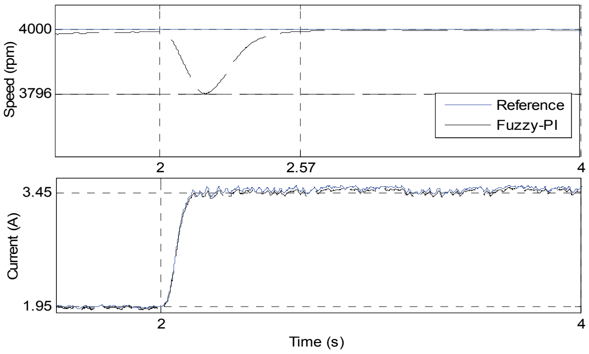


Fig. 13. The speed-time and current-time responses of fuzzy PI controller in sudden loaded operating condition

As seen in Fig. 12, in the speed control implemented by PI controller of DCSM for the sudden loaded operating condition, there were a negative overshoot of almost 8.1% during 0.59 seconds before the motor caught the reference value. In this operating condition, the maximum motor current was 3.45 A. As seen in Fig. 13, in the speed control implemented by the cascade fuzzy PI controller of DCSM for the sudden loaded operating condition, the reference value was reached during 0.57 seconds, and there was a negative overshoot of almost 5.1%. In this case, the motor current was 3.44 A.

## VI. Conclusions

In this experimental study, traditional PI and cascade fuzzy PI controllers were designed to control the speed and torque of DCSM in different operating conditions. In the dynamic operating conditions, the cascade fuzzy PI controller provided a higher performance than traditional PI controller because of dynamically adjusting its coefficients. It showed that the cascade fuzzy PI controller was less affected from the non-linear changes than the traditional PI controller. Deviation from the reference speed in the sudden loaded condition was almost 8.1% and 5.1% for the traditional PI and the cascade fuzzy PI controllers, respectively. In addition, the cascade fuzzy PI controller reached to the reference speed faster than the other, and the oscillations occurring during reaching to the reference speed was less when comparing with the traditional PI controller. We observed that the current control and thus the torque control of the cascade fuzzy PI controller for all operating speeds and loads were better than those of the traditional PI controller.

As a result, the speed and torque controls implemented by using the cascade fuzzy PI controller improved the performance of DCSMs.

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