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ANGLE POSITION CONTROL OF FUZZY ALGORITHM WITH VARIABLE SCALE FACTOR FOR SRM

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Abstract. *Based on fuzzy algorithm and proportional-integral (PI) controller, a strategy of angle position control (APC) is presented in this paper. The main characteristic of this method is that the scale factor of the fuzzy controller is computed by PI controller. The turn-on angle is adjusted online by PI controller and fuzzy controller. Then the APC is achieved to drive the switched reluctance motor (SRM) at a high speed. Thus, the difficulty of making a nonlinear math model for SRM is solved. The polynomial fitting is applied to analyzing the impact of the turn-on angle on the performance of SRM. The inductance-torque-current-angle data of 12/8 pole SRM is obtained through finite element method. Experimental results show that the SRM has a good dynamic performance. The method is implemented on a platform for 11kW SRM with a DSP2812 controller. Experimental results demonstrate the effectiveness of the presented strategy.*

Keywords: Angle position control, Fuzzy factor, Turn-on angle, Switched reluctance motor

1. **Introduction.** Switched reluctance motor is a latest step-less speed system. It is suitable for the condition of high speed owing to the simple structure. Thus, the method of angle position control (APC) is researched to control the switched reluctance motor (SRM) at high speed. However, the doubly salient pole structure leads to the non-linearity of magnetic saturation, eddy current and hysteresis [1]. The mathematical model of SRM is difficult to establish. The turn-on angle adjusted off-line by a linear or quasi-linear model at high speed could not satisfy the performance of SRM. Hence, it is very necessary to optimize the method of APC in order to improve the accuracy and rapidity of the turn-on angle.

At present, some researches have been done on the optimization of the turn-on angle. The phase current and turn-off angle were used to adjust the turn-on angle by a proportional-integral (PI) controller in [2]. Yang et al. obtained different motor performances by changing the value of switch on-off angles [3]. Thus, a theoretical basis of selecting the angle was provided. A new approach based on speed and current of the motor to achieve the adaptive adjustment of the turn-on angle was proposed by Sozer et al. [4]. The turn-on angle was adjusted without the need for motor parameters. An encoder with a simple circuit was applied to selecting the turn-off angle in [5]. This method was not interfered by the sampling-period of a microprocessor and the speed of SRM. Conventional method was utilized to calculate the turn-on angle online in [6, 7, 8]. An experienced equation was used to compute the turn-on angle. Beno et al. presented a strategy of adaptive fuzzy algorithm based neural network to optimize switch on-off angle [9]. The strategy is suitable for various ratings of SRM driver. The turn-on angle predicted by the least squares method was adjusted online in [10]. This method aimed to get minimum current at demanded torque. The switch on-off angle was optimized to maximize the average torque in [11]. The angle was selected by look-up table method. An optimized scheme of switched angle was presented in [12]. The scheme depends on the accuracy of current, voltage and rotor position.

In these methods, the turn-on angle is only adjusted by off-line, PI control or fuzzy algorithm to implement the method of APC. However, the performance of nonlinear control for SRM is difficult to satisfy. Some sophisticated algorithms such as neural networks, genetic algorithm are applied to APC. However, the complexity of the system is increased and the response rate of the system is reduced. Therefore, it is necessary to research a simple method which is effective and easy to realize.

A strategy of APC based on PI-fuzzy algorithm is presented in this paper. Different from the traditional fuzzy-PI [13, 14], the PI is applied to computing the scale factor of fuzzy algorithm. Then the turn-on angle is adjusted by PI controller and fuzzy controller simultaneously. The fuzzy algorithm with variable scale factor not only adjusts the turn-on angle accurately and quickly, but also fulfills the performance for SRM nonlinear system. Simulation and experiment demonstrate the effectiveness of the presented strategy.

This paper is organized as follows. Following the Introduction, the effect of turn-on angle on the performance of SRM is analyzed in Section 2. The implementation of the APC based on PI-fuzzy algorithm is described in Section 3. The simulation results are shown in Section 4. The experimental results are shown in Section 5. The conclusions are presented in Section 6.

2. **Analysis of the Effect of Turn-on Angle on SRM.** The control of SRM could be achieved by adjusting turn-on angle. The relationship between the turn-on angle and energy is discussed in [15]. A method of polynomial fitting is proposed to analyze the effect of turn-on angle on the SRM in this paper. Firstly, inductance-angle curves at different current are obtained by the finite element method in Figure 1. Then the polynomial fitting method is applied to obtaining the fitted curve and the nonlinear equation $L(\theta)$ of a phase inductance. Here, I = 2A. The fitted inductance curve is showed in Figure 2.

$$L(\theta) = -10^{-9}\theta^6 + 10^{-7}\theta^5 - 6 \times 10^{-6}\theta^4 + 0.001\theta^3 - 0.0006\theta^2 + 0.0012\theta + 0.0062 \quad (1)$$

As discussed in [16], when a phase winding of SRM is energized, the stator resistance is ignored, and the balanced voltage equation could be expressed as

$$\frac{U_S}{\omega_r} = L\frac{di}{d\theta} + i\frac{dL}{d\theta} \quad (2)$$

where U_S is the DC voltage of the motor, ω_r is the motor speed, L is phase inductance, and i is phase current.

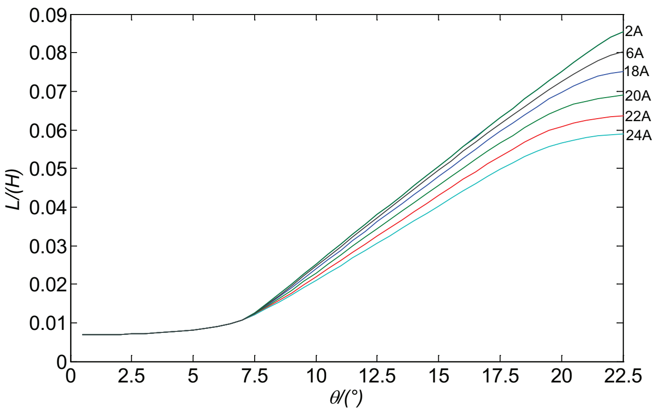


FIGURE 1. Inductance characteristics for the SRM

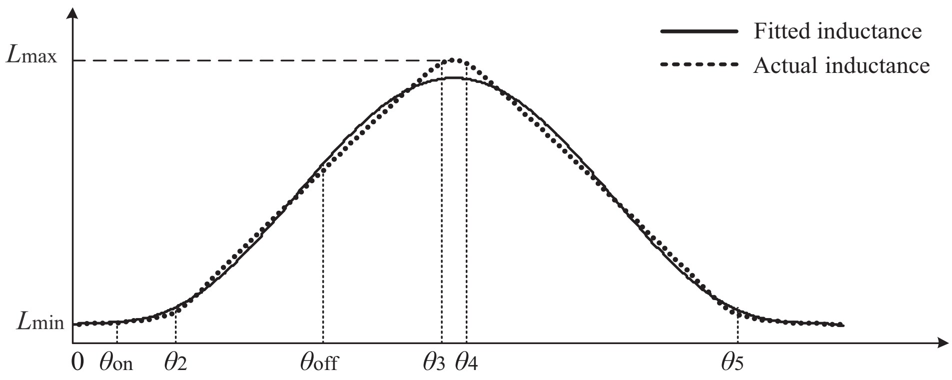


FIGURE 2. Fitted and actual inductance (I = 2A)

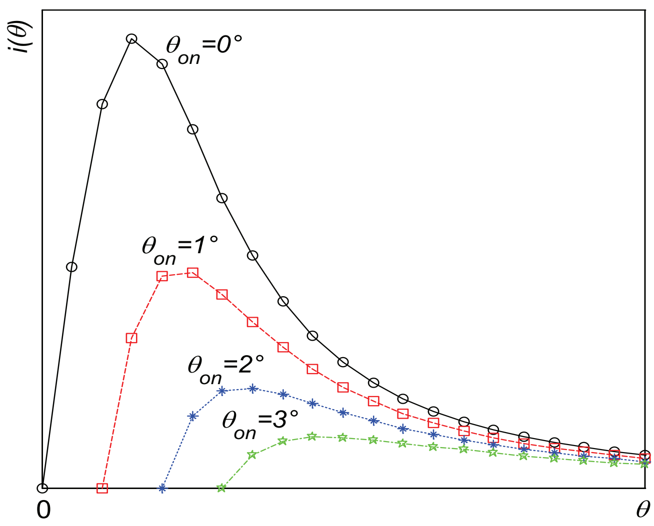


FIGURE 3. Current in different turn-on angles

Combining Equation (1) and Equation (2), then the integral operation respect to θ is used, and a new voltage equation could be written as

$$\frac{U_S}{\omega_r}\theta + C = L(\theta)i \tag{3}$$

The initial condition $i(\theta_{on}) = 0$ is substituted into Equation (3) and the integration constant C could be computed as

$$C = -U_S\theta_{on}/\omega_r \tag{4}$$

where θ_{on} is turn-on angle. Combining Equation (3) and Equation (4), the current equation in the condition of nonlinear inductance could be written as

$$i(\theta) = \frac{U_S\left(\theta - \theta_{on}\right)}{\omega_r L(\theta)} \tag{5}$$

The rotor position of 0 degree is defined in [17], where stator salient pole and rotor salient pole are under the condition of non-facing. Then the turn-on angle of 0 degree, 1 degree, 2 degree and 3 degree are substituted into Equation (5) respectively and the current curves are generated with different turn-on angles in Figure 3. As shown in Figure 3, the peak and root-mean-square (RMS) of current are obviously different, the smaller the turn-on angle is, the greater the peak of current is. The electromagnetic torque is proportional to square with secondary of phase current. It will directly affect the output of the torque. Therefore, a strategy of adjusting the turn-on angle to change the RMS and peak of current is effective to achieve the method of APC. The turn-on angle is significant to improve the performance of SRM.

3. **Implementation of the APC with Variable Fuzzy Scale Factor.** As seen that the effect of turn-on angle on SRM is obvious in the previous section. Therefore, a suitable method needs to be applied to achieving the method of APC. Fuzzy algorithm is suitable for nonlinear system. However, it adjusts the turn-on angle for SRM discretely. The PI controller is utilized to control SRM at a high speed in [18], but the characteristic of the PI controller leads to the limitation for nonlinear system. Therefore, fuzzy algorithm controller and PI controller are combined in this paper. The scale factor of fuzzy algorithm is calculated by PI controller. The value of turn-on angle is determined by the scale factor and the output of fuzzy simultaneously. The equation of turn-on angle could be expressed as

$$\theta_{on} = ku * U + \frac{\theta_H + \theta_L}{2} \tag{6}$$

where ku is scale factor, U is the output of fuzzy controller, θ_H is upper limit of the turn-on angle, and θ_L is the lower limit of the turn-on angle.

The speed error is the input of controller. ku can be expressed as

$$ku = kp * e(t) + ki * \int e(t)dt \tag{7}$$

where $e(t)$ is speed error, kp is a proportional constant, and ki is integral constant.

Equation (6) and Equation (7) show that the fuzzy algorithm with variable scale factor computed by PI can obtain precise turn-on angle. Figure 4 illustrates the block diagram for the presented control strategy.

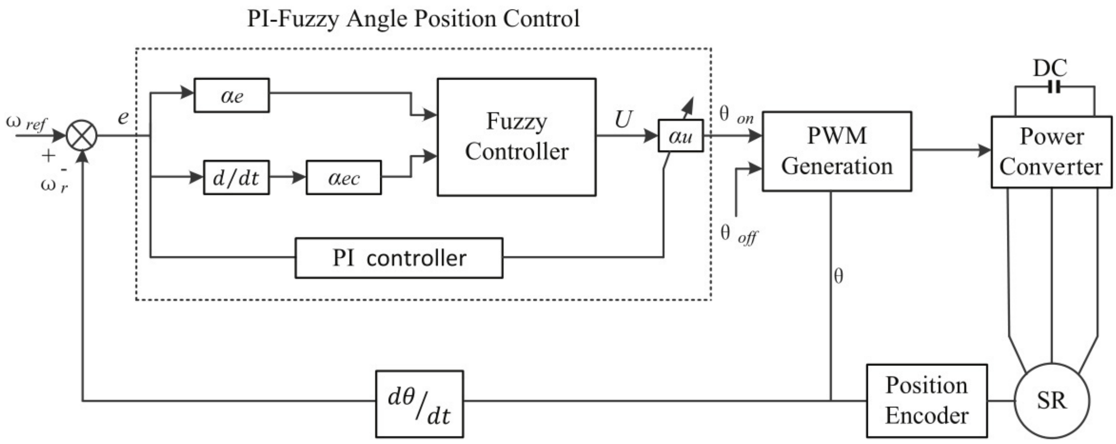


Figure 4. Control system of SRM

In Figure 4, α_e is quantization factor of speed error, and α_{ec} is quantization factor of speed error derivative. α_e and α_{ec} are set to be constant to decrease the complexity of the system in this paper. E^*, EC^*, U^* are fuzzy variables of α_e, α_{ec} and turn-on angle respectively. The fuzzy subset of E^*, EC^*, U^* is

$$U^* = E^* = EC^* = \{NB, NM, NS, ZE, PS, PM, PB\}$$

The fuzzy rule-table is shown in Table 1 and it is a summary of practical experience and theoretical knowledge of experts [19]. It can be seen from Table 1, when the E^*, EC^*, are negative large value, the U^* is a positive large value, and the turn-on angle could be adjusted fast. The fuzzy domain of E^*, EC^*, U^* is $[-7, 7]$; hence, the turn-on angle could be adjusted more accurately.

TABLE 1. Fuzzy control rules

U^* \ EC^* / E^*	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PB	PB	PM	ZE	ZE
NM	PB	PB	PB	PB	PM	ZE	ZE
ZS	PM	PM	PM	PM	ZE	NS	NS
NE	PM	PM	PS	ZE	NS	NM	NM
PS	PS	PS	ZE	NM	NM	NM	NM
PM	ZE	ZE	NM	NB	NB	NB	NB
PB	ZE	ZE	NM	NB	NB	NB	NB

The fuzzy matrix R^* contained in Table 1 is expressed as

$$R^* = \wedge_{ij} \left(E_i^* \times EC_j^* \right) \times U_{ij} \tag{8}$$

The centre of gravity method is used for defuzzification. The output of each fuzzy element and its corresponding membership in R^* are used to compute the weighted average. Then the accurate output of fuzzy is expressed as

$$U = \frac{\sum_i u\left(R_i^*\right) R_i^*}{\sum_i u\left(R_i^*\right)} \tag{9}$$

where $u(R_i^*)$ is membership. Equation (9) is substituted into Equation (6) and Equation (7). Then the actual turn-on angle is obtained. Therefore, the method of APC with variable fuzzy scale factor is achieved for SRM driver.

4. **Simulation.** The torque-inductance-current-angle data of 11kW, 12/8 pole SRM was obtained by finite element method. In order to verify the effectiveness of the APC with variable fuzzy scale factor, simulation model based on the data was built. The main parameters of the SRM are shown in Table 2.

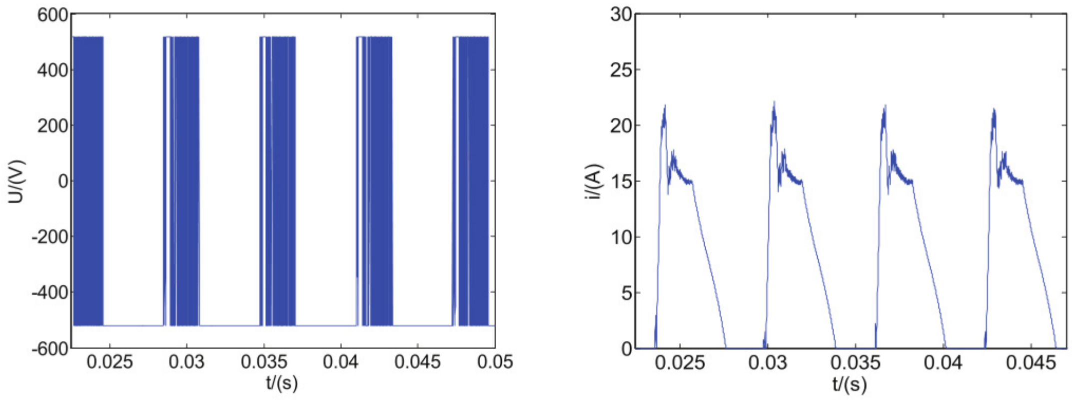
TABLE 2. Fuzzy control rules

Parameter	*Value*
Rated voltage	520V
Rated current	25A
Rated speed	1000r/min
Maximum speed	1500r/min

Simulation is operated up the rated speed due to the fact that the method of APC is suitable for high-speed. The turn-off angle is set to be 17 degree. The load torque is 30N.m and the speed is 1200r/min. The steady-state voltage and current of the SRM are shown in Figure 5. The adjustment process of turn-on angle is shown in Figure 6.

Simulation results demonstrate that the phase voltage and current are steady. The turn-on angle is adjusted online. As a conclusion, the SRM operates smoothly at steady-state.

In order to verify the superiority of the presented strategy, the method of APC based on fuzzy algorithm is compared to the presented strategy. The speeds of the SRM based on PI-fuzzy algorithm and fuzzy algorithm are shown in Figure 7. Figure 7 shows that the presented SRM driver responds faster. The fluctuation and overshoot of speed are smaller. The torque of the SRM based on PI-fuzzy algorithm and fuzzy algorithm is



(a) (b)

FIGURE 5. Performance of SRM: (a) a phase voltage and (b) a phase current

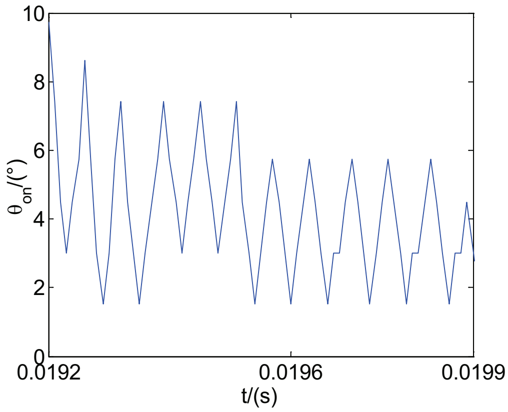


FIGURE 6. Turn-on angle of SRM

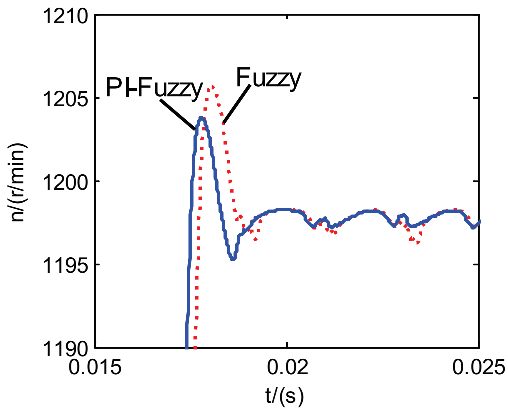
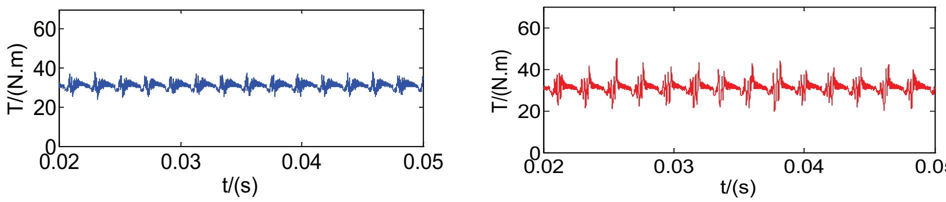


FIGURE 7. The comparison of speed



(a) (b)

FIGURE 8. The comparison of torque: (a) PI-fuzzy algorithm and (b) fuzzy algorithm

shown in Figure 8(a) and Figure 8(b) respectively. Figure 8 shows that the torque ripple could be reduced well by the presented method.

Simulations of variable load and speed have been implemented to verify the dynamic characteristics of the SRM. The response waveforms of torque and speed are shown in Figure 9.

The load torque is increased from 30N.m to 50N.m transiently in Figure 9(a) at 0.03s. It could be seen that the SRM operates steadily at different load torque. In addition, the SRM comes to steady state apace when the torque is changed. The demanded speed is increased from 1200r/min to 1500r/min transiently in Figure 9(b) at 0.05s. It shows that the speed of SRM is controlled effectively in both transient and steady state.

5. **Experiment.** The presented method has been implemented on the experimental platform as shown in Figure 10. A digital signal processor DSP2812 is used for verifying the

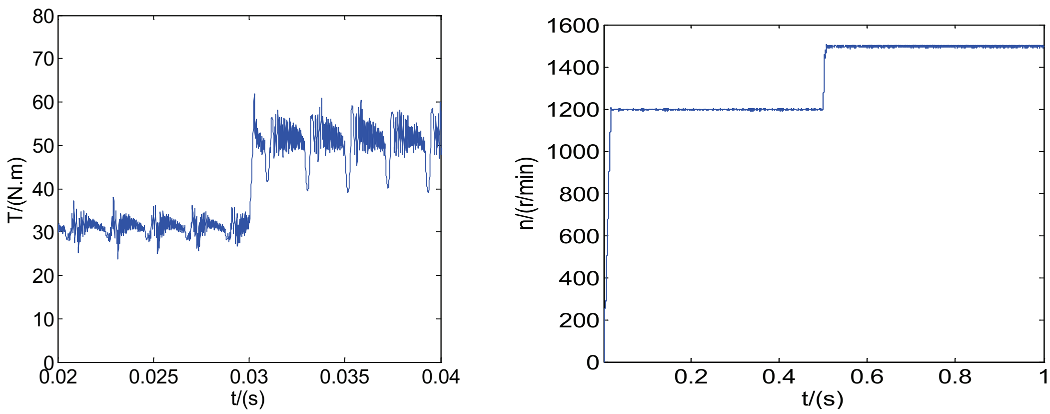


Figure 9. Dynamic characteristic of SRM: (a) torque and (b) speed

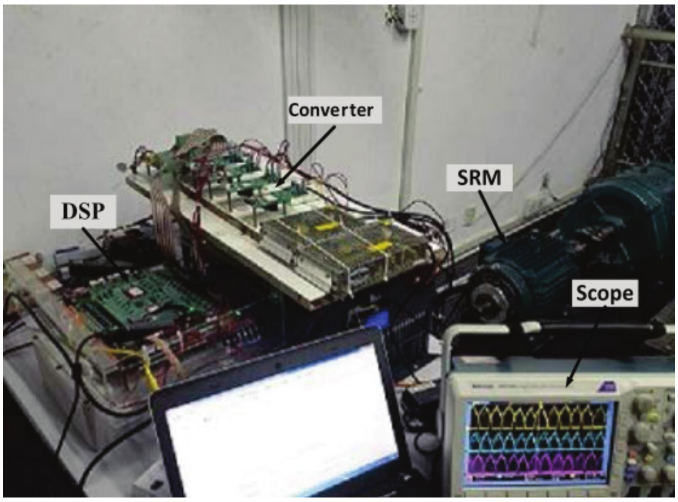


Figure 10. Hardware platform of system

feasibility of the method. DSP2812 is suitable for control field owing to the enhanced features. The topology of the power converter is three-phase asymmetrical half-bridge. An encoder is utilized to detect the actual speed.

The SRM is operated at the demanded speed of 1200r/min. The three-phase current waveforms are shown in Figure 11. It could be seen that the three phase windings are conducted normally. The distortion of the three-phase current is small.

The steady-state torque waveform in the condition of light load is shown in Figure 12. It could be seen that the torque changes from 4.6N.m to 5N.m. The steady torque performance of the SRM at demanded load of 32N.m is shown in Figure 13. The torque changes from 31.6N.m to 33.2N.m. Both of the torque ripples in Figure 12 and Figure 13 are small. Therefore, the experimental SRM could operate steadily with different loads. Hence, the proposed method is demonstrated to be effective.

6. **Conclusions.** In this paper, the polynomial fitting method is utilized to analyze the effect of turn-on angle on SRM. The drive system for SRM is designed based on the method of APC. The fuzzy algorithm and PI controller are combined to achieve the method of APC by adjusting the turn-on angle. In this method, the scale factor of fuzzy algorithm is computed by PI controller. Various kinds of simulations are implemented to verify the performance of the SRM. These included the operation of steady state current and torque, transient changes in torque and speed. In addition, the presented control system

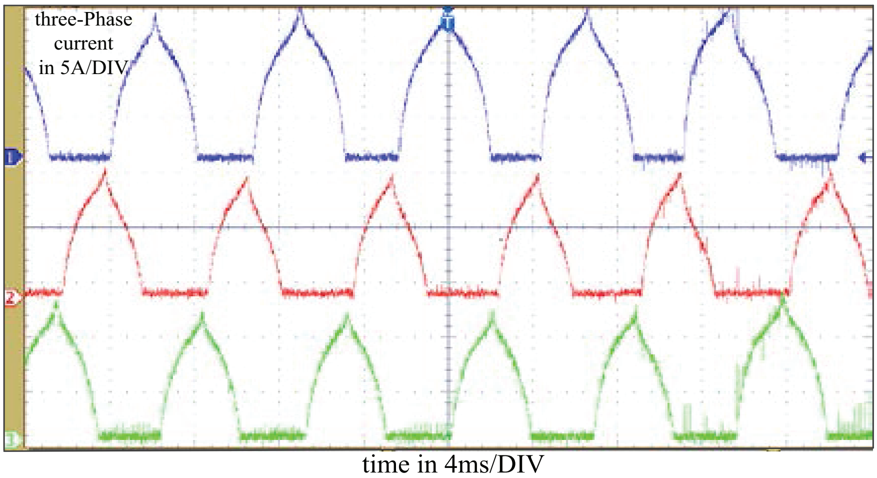


Figure 11. Experimental current

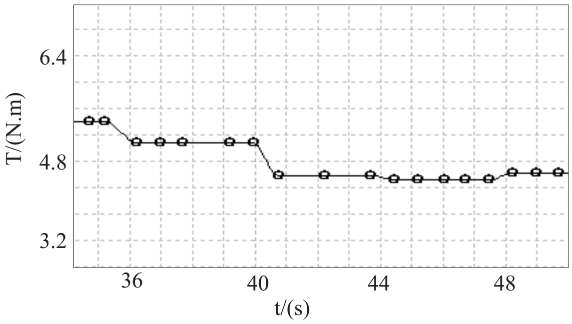


Figure 12. Steady-state torque at light load

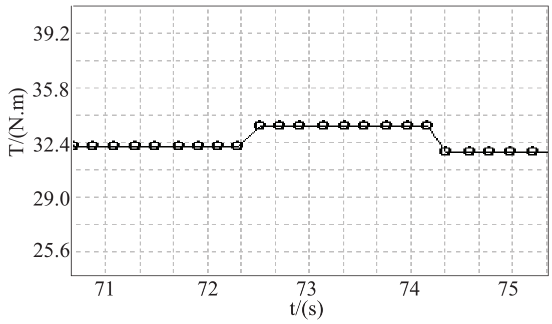


Figure 13. Steady-state torque at demanded load of 32N.m

is implemented on a DSP2812 hardware platform. The effectiveness of the strategy is demonstrated by experiments. The experimental results show that the control system for SRM has a steady performance.

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