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Flux Weakening Control for Stator-Doubly-Fed Doubly Salient Motor

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Abstract

To satisfy the demands of electric vehicles (EVs) of fast torque response in wide range of velocity, the principle of flux weakening of the stator-doubly-fed doubly salient (SDFDS) motor which is designed for EVs has been studied and analyzed. And its advantage of regulating the field flux independently has been fully utilized. The flux weakening strategy is proposed and high performance of SDFDS motor drive is acquired at high speed. Simulation and experiment are carried out based on Matlab/Simulink and experiment platform. The simulation and experimental results with good speed adjusting performance verify the effectiveness of the flux weakening control strategy of SDFDS motor drive.

Keywords: Stator-Doubly-Fed doubly salient motor, flux weakening, speed control, EVs

1 Introduction

As energy crisis and environment pollution are increasingly intensified over the world, the electric vehicles (EVs) become the competitive substitute for gasoline vehicles which consume lots of oil and exhaust emissions [1]. In order to enable EVs directly competing with gasoline vehicles, the aims of the EV motor drive are to pursue high efficiency over wide speed range, high power density, high controllability, high reliability and maintenance free operation [2]-[6]. As so far, four types of motor drives have been applied to EVs. They are brushed DC motor drives, induction motor (IM) drives, PM synchronous or PM brushless motor drives, and switched reluctance motor (SRM) drives [2]-[3]. As a novel motor designed for EVs, the stator-doubly-fed doubly salient (SDFDS) motor [4]-[5], [7] has the feature of regulating the field flux independently and effectively, which makes the implementations of the flux weakening for expanding the speed range and on-line efficiency optimization easier than other motors [8]-[9]. Fig.1 shows the cross-section of a 3-phase 12/8-pole SDFDS motor.

The back electromagnetic force (EMF) becomes so big when the motor is at high speed that the flux has to be weakened for speed increasing. The rotor flux of induction motor is in inverse proportion to speed for flux weakening [10]. As for PM synchronous motors [11], the demagnetizing current i_d is obtained by flux-weakening characteristics as a function of the operating speed. Prior angle control is used for PM brushless motors to increasing the motor speed [12]. And the conduction angle is adjusted for high speed running as to the switched reluctance motor [13]. The advantage of the SDFDS motor of regulating the field flux independently has been fully utilized in this paper. The flux weakening strategy is proposed and high performance of the SDFDS motor drive is acquired at high speed. Both simulation and experiment are carried out. Good speed adjusting performance is achieved, verifying the effectiveness of the flux weakening control system of the SDFDS motor drive.

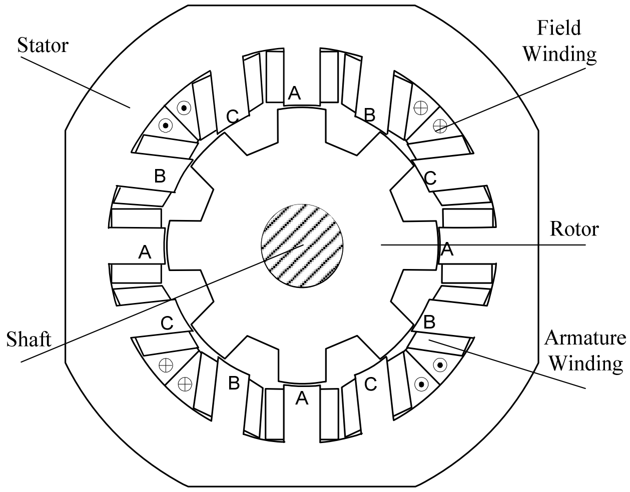


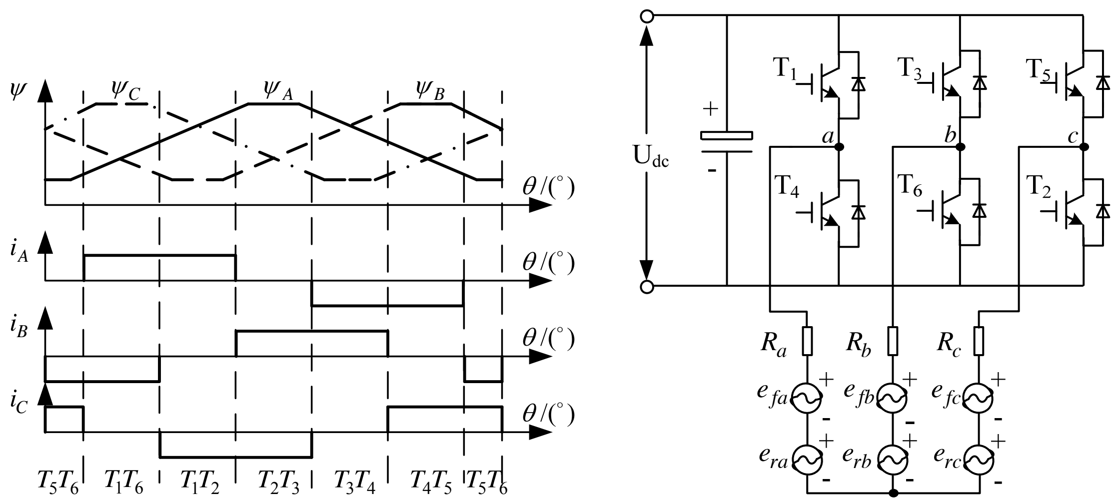
Figure 1: Cross-section of the 12-8 pole SDFDS motor

2 Principle Analysis of Flux Weakening

Three phase full bridge circuit and its conduction principles used for the SDFDS motor drive is shown in Fig. 2, where the piecewise linear inductance model is utilized so as to make it easy to analyze the SDFDS motor drive. The voltage equation of the SDFDS motor is shown as follows:

$$\begin{aligned} U_p &= i_p R_p + e_{bp} \\ &= i_p R_p + e_{fp} + e_{rp} \end{aligned} \tag{1}$$

where, $e_{bp} = e_{fp} + e_{rp}$ is the total back electromagnetic force, $e_{fp} = i_f \frac{dL_{pf}}{d\theta}\omega$ is the back electromagnetic force of field excitation, $e_{rp} = i_p \frac{dL_p}{d\theta}\omega$ is the back electromagnetic force of reluctance; U_p, i_p, and R_p are phase voltage, phase current and winding resistance, respectively. L_p, L_{pf},, and i_f are phase self-inductance of armature winding, mutual-inductance between armature winding and field winding, and field current, respectively. And ω, and θ are rotor angular velocity and rotor position angle, respectively.



(a) Commutating mode (b) three-phase full-bridge converter

Figure 2: Three phase full bridge circuit and its conduction principles

According to the operation principles of the SDFDS motor, the electromagnetic torque of phase p (p =A, B, C) can be expressed as:

$$
\begin{aligned}
T_p(\theta,i) &= T_{rp} + T_{fp} \\
&= \frac{1}{2} i_p^2 \frac{\partial L_p}{\partial \theta} + i_p i_f \frac{\partial L_{pf}}{\partial \theta} \\
&\approx i_p i_f \frac{\partial L_{pf}}{\partial \theta}
\end{aligned} \tag{2}
$$

where, $T_{rp} = \frac{1}{2} i_p^2 \frac{\partial L_p}{\partial \theta}$ is the reluctance torque; $T_{fp} = i_p i_f \frac{\partial L_{pf}}{\partial \theta}$ is the field torque. The field torque T_{fp} is much larger than the reluctance torque T_{rp}, thus the electromagnetic torque $T_p(\theta,i)$ can be simplified as T_{fp}.

As the voltage equation (1) showed, when the speed rises, the back electromagnetic force e_{bp} increases correspondingly. As the phase voltage of armature winding U_p is fixed, the armature current i_p decreases, which makes the electromagnetic torque T_p reduce. And the mechanical movement equation of the SDFDS motor is:

$$
T_e = J \frac{d\omega}{dt} + B\omega + T_l \tag{3}
$$

where, T_e is the total electromagnetic torque, $T_e = T_A + T_B + T_C$, J is the rotational inertia, B is the friction coefficient and T_l is the load torque. According to (3), the motor speed $\omega = \frac{T_e - T_l}{B}$ at the steady state, namely the steady state motor speed depends on the total electromagnetic torque T_e. Based on the above analysis, the increase of back electromagnetic force makes the decrease in phase current when the motor works at high speed. Thus the total electromagnetic torque T_e minishes, which restrain the rise of motor speed.

Hence, the motor flux has to be weakened in order to extend the range of speed. As for the SDFDS motor, the flux weakening control can be attained easily by regulating the field current i_f, as compared to other motors.

3 Flux Weakening Strategy for SDFDS Motor

Fig.3 shows the simulated output torque characteristics versus field current i_f at the speeds of 2000，2500，3000 r/min. It can be seen that as the field current decreases, the output electromagnetic torque first increases and then decreases. Thus the speed also first increases and then decreases when the field current decreases. Hence, the key of flux weakening control for the SDFDS motor is to get the field current $I_f^{T_{e\max}}$ at which the electromagnetic torque reach the peak value. Then the flux weakening component I_f^{Δ} is proportional to electromagnetic torque approximately when the field current $I_f \in [I_f^{T_{e\max}}, I_{fN}]$. Then the conventional PI regulator can be used to realize flux weakening for extending the range of speed.

Based on the above analysis, the flux weakening control strategy of the SDFDS motor can be developed as follows:

I. When the reference speed of motor n_{ref} is less than or equal to the rated speed n_N, the standard motor control of regulating the speed is adopted;

II. When the reference speed of motor n_{ref} is higher than the rated speed n_N, the flux weakening control strategy is adopted for regulating the speed:

① When the feedback speed n_{fb} is less than or equal to the rated speed n_N, the standard motor control of regulating the speed is adopted；

② When the feedback speed n_{fb} is higher than the rated speed n_N, the flux weakening control strategy is adopted. The reference armature current is set to be the nominal value i_{pN}, and the flux weakening component I_{fRef}^{Δ} depends on the output of speed PI regulator. The reference value of field current is $i_{fRef} = i_{fN} - I_{fRef}^{\Delta}$, and its upper limit is $I_f^{T_{e\max}}$. I_{fRef}^{Δ} can be obtained by

$$i_{fRef}^{\Delta}(k) = i_{fRef}^{\Delta}(k-1) + k_p e_n(k) + k_i \Delta e_n(k) \qquad (4)$$

The control configuration of flux weakening control strategy of the SDFDS motor drive at high speed is shown in Fig. 4.

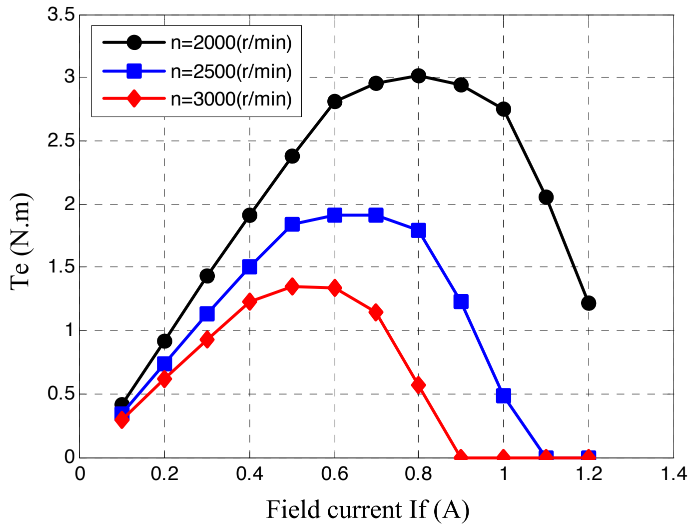


Figure 3: Curve of output torque and field current under different speed

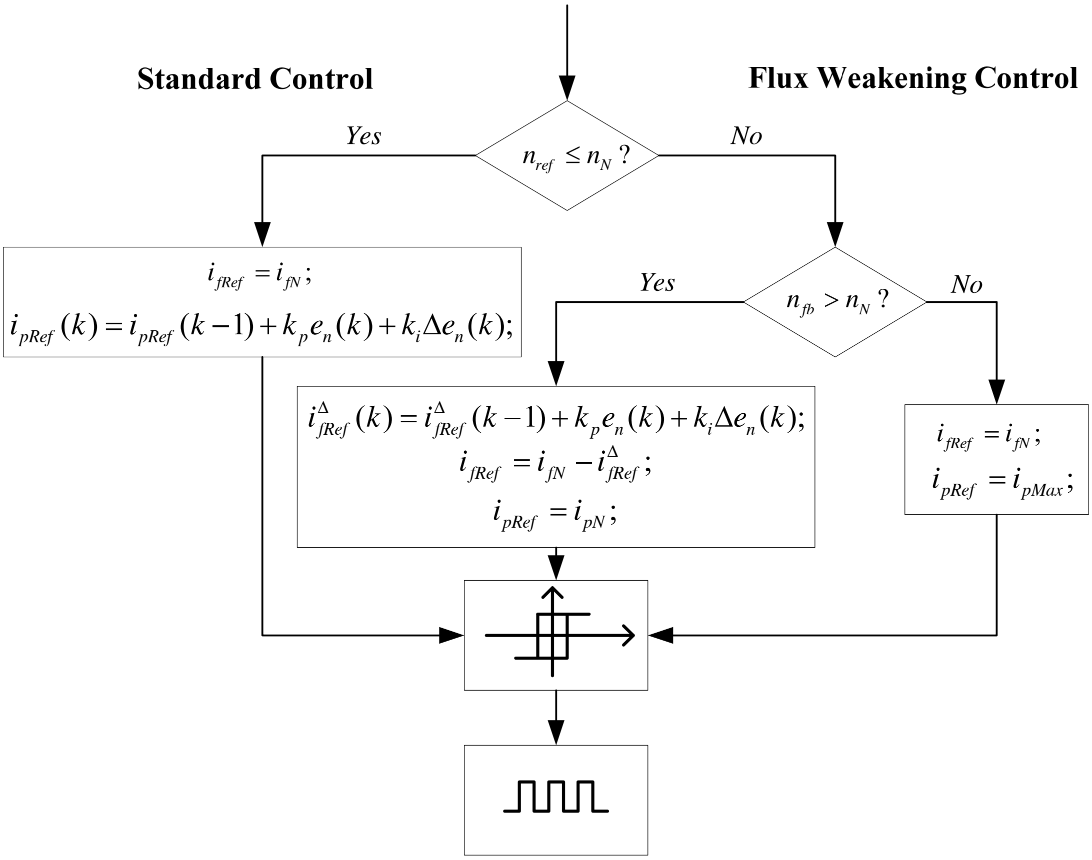


Figure 4: Control configuration of flux weakening control strategy of SDFDS motor drive

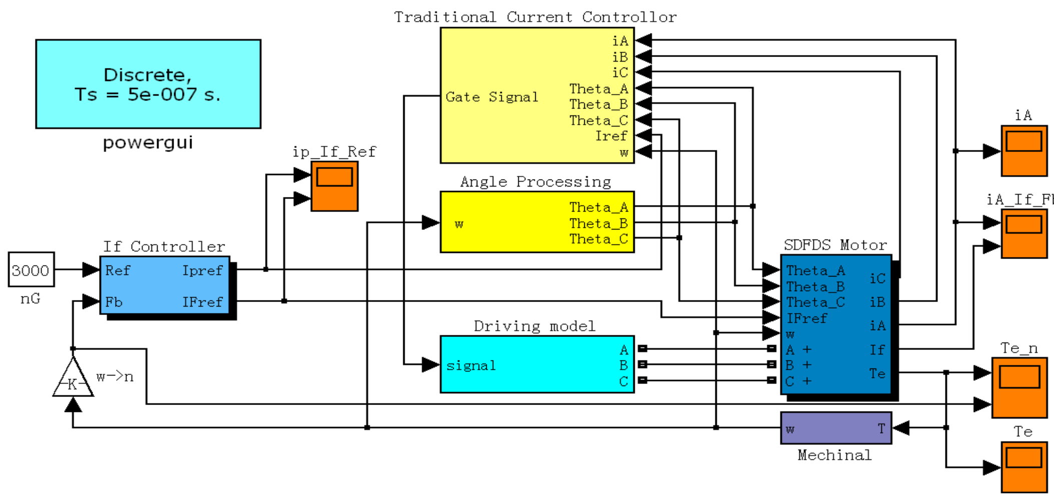


Figure 5: Simulation model of flux weakening control of SDFDS motor drive at high speed

4 Simulation

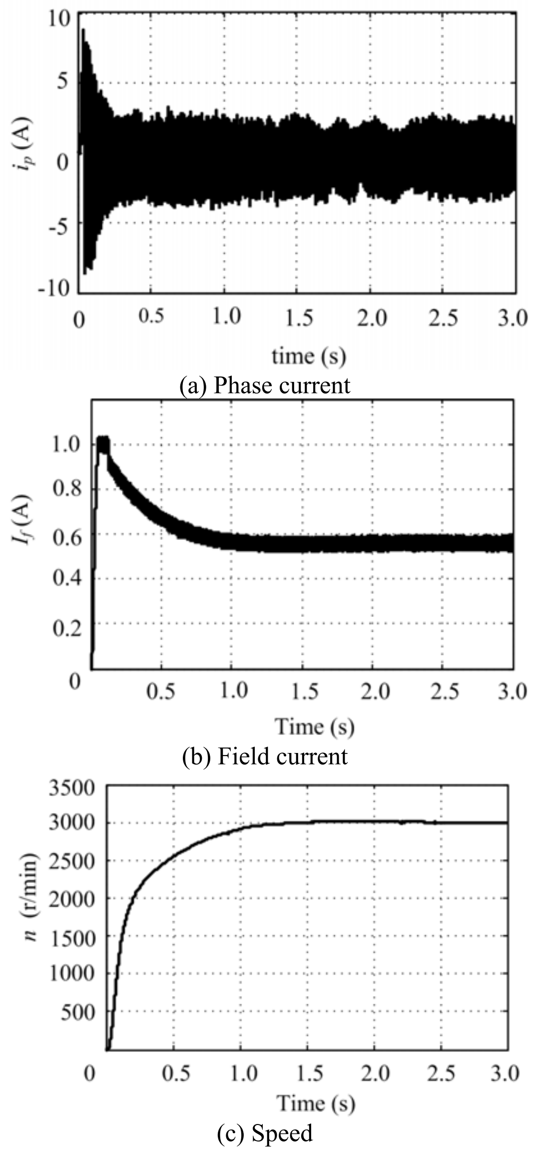
In order to verify the effectiveness of the proposed flux weakening control scheme, a simulation model is developed in Matlab/Simulink software, as shown in Fig. 5.

When the reference speed is 3000 r/min at no load, the armature current, field current, and step response curve of speed are shown in Fig. 6 under the flux weakening control strategy.

As illustrated in Fig. 6, the speed of SDFDS motor can reach the reference value rapidly and there is no steady speed error. The good speed adjusting performance is achieved when the proposed field weakening control strategy is used.

5 Experimental Results

In order to further investigate the effectiveness of the proposed field weakening control strategy and to verify the theoretical simulation, a prototype of the SDFDS machine has been designed and fabricated, as shown in Fig. 7. The main design data of the prototype are listed in Table 1. The experimental setup consists of a 3-phase 12/8-pole SDFDS motor with its stator connected to an IGBT-based PWM converter. A TMS320F2812 DSP based digital control platform is designed for implementing efficiency optimal algorithm. The block diagram of flux weakening control and experimental system are shown in Fig. 8 and Fig. 9, respectively.



(a) Phase current

(b) Field current

(c) Speed

Figure 6: Simulation curves of flux weakening control

The experiments on the prototype machine were carried out at the same operating point as the simulation. Comparing Fig. 10 with Fig.6 shows that the experimental results agree with simulated results well, verifying the effectiveness of the proposed scheme.

Figure 7: Prototype machine

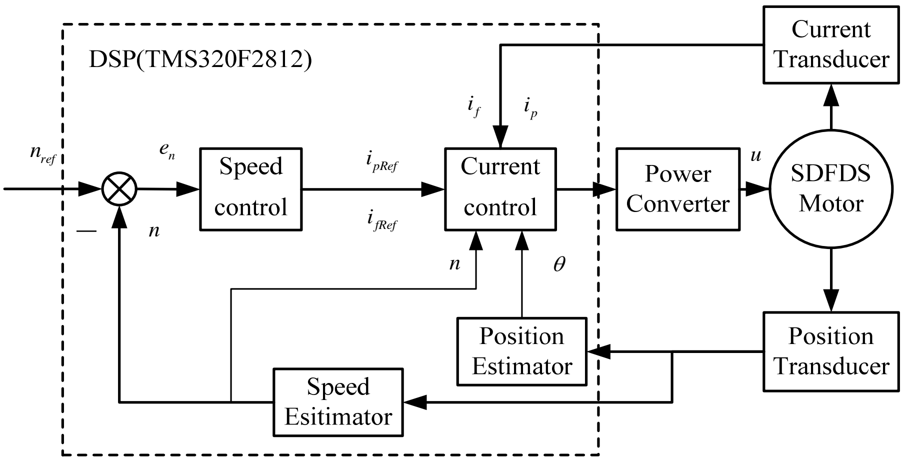


Figure 8: Block diagram of flux weakening control of the SDFDS motor drive

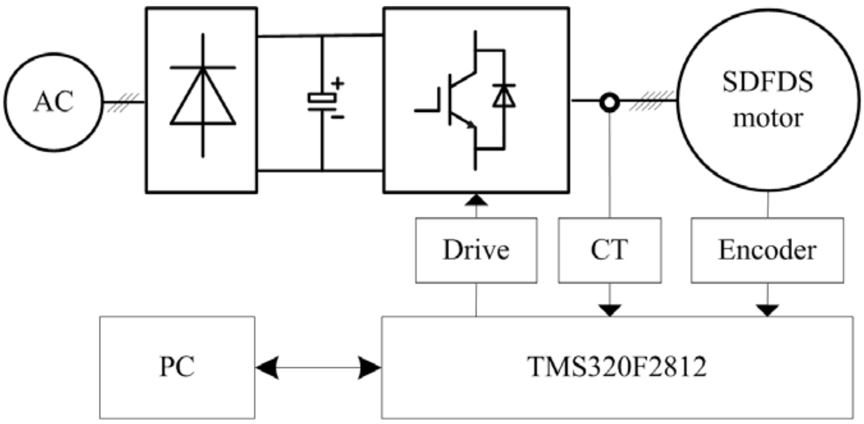
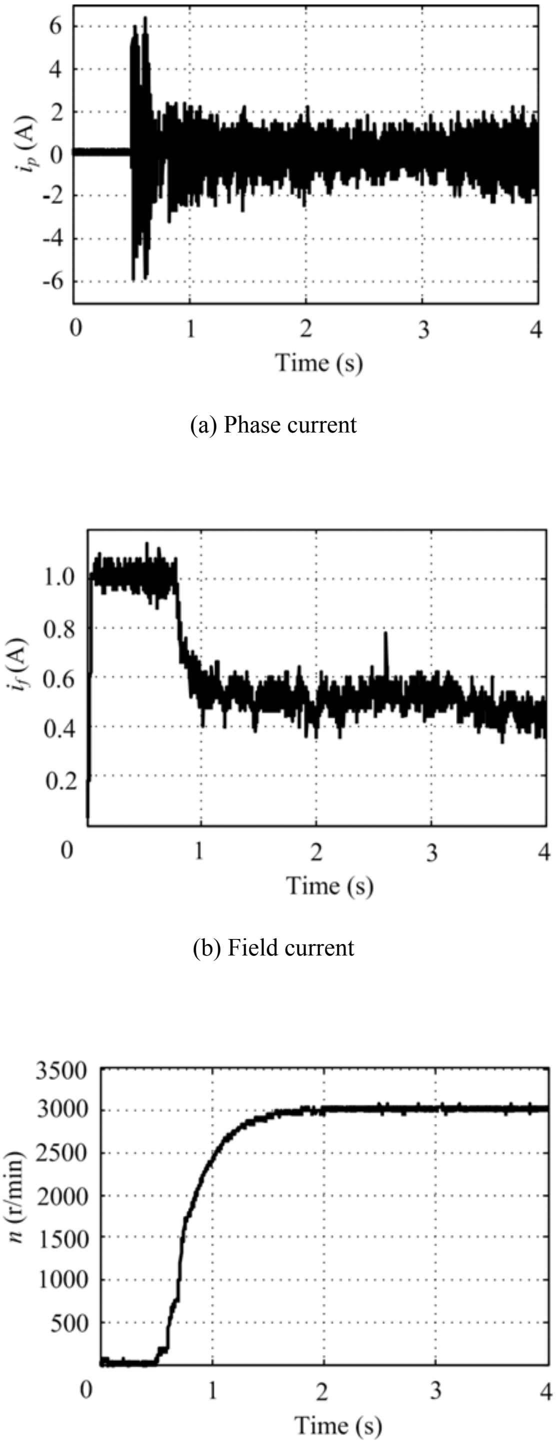


Figure 9: Schematic diagram of the SDFDS motor drive



(a) Phase current

(b) Field current

(c) Speed

Figure 10: Measured curve of flux weakening control

Table 1 Main design data of the prototype machine

Items	Parameter
Rated power	750W
Rated voltage	190V
Reated field voltage	70V
Rated phase current	6A
Rated field current	1A
Armature resistance/phase	0.62Ω
Field winding resistance	19Ω
Number of stator pole	12
Number of rotor pole	8
Number of phase	3
Rated torque	4.77Nm
Rated speed	1500 r/min

6 Conclusion

In this paper, the principle of flux weakening of the SDFDS motor has been studied and analyzed. The flux weakening strategy is proposed to satisfy the demands of fast torque response in wide range of velocity for EVs. Based on Matlab/Simulink and experiment platform, simulation and experiments are carried out to realize the flux weakening control of the SDFDS motor drive at high speed. And good speed adjusting performance is achieved, which verify the effectiveness of the flux weakening control strategy for the SDFDS motor drive.

Acknowledgement

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References

[1] C.C. Chan, *The State of the Art of Electric, Hybrid, and Fuel Cell Vehicles*, Proceedings of the IEEE, 2007, Vol. 95, No. 4, 2007, pp. 704 – 718.

[2] X.D. Xue, K. Cheng, N.C. Cheung, *Selection of electric motor drives for electric vehicles*, Australasian Universities Power Engineering Conference, Australasian, 2008, pp. 171-176.
[3] G. Nanda, N.C. Kar, *A Survey and Comparison of Characteristics of Motor Drives Used in Electric Vehicles*, Electrical and Computer Engineering, CCECE '06, Canada, May 2006, pp. 811-814.
[4] Ming Cheng, Ying Fan and K.T. Chau, *Design and analysis of a novel stator-doubly-fed doubly salient motor for electric vehicles*, Journal of Applied Physics, May 2005, Vol. 97, No. 10, May 2005, pp. 10Q508-1-3.
[5] Ying Fan and K.T. Chau, *Design, modeling and analysis of a brushless doubly-fed doubly-salient machine for electric vehicles*, International Conference on Electrical Machines and Systems (ICEMS2005), 2005, Vol. I, pp. 614-619.
[6] K.T. Chau, C.C. Chan, Liu Chunhua, *Overview of permanent-magnet brushless drives for electric and hybrid electric vehicles*, IEEE Transactions on Industrial Electronics, Vol. 55, No. 6, 2008, pp. 2246 - 2257.
[7] Ming Cheng, Wei Hua, Jianzhong Zhang and Wenxiang Zhao, *Overview of stator-permanent magnet machines*, IEEE Transactions on Industrial Electronics, November 2011, Vol. 58, No. 11, pp. 5087-5101.
[8] Xiangxin Kong, Ming Cheng, Yagang Shu, *Flux-weakening control of constant power of stator-doubly-fed doubly salient motor for electric vehicles*. Proceedings of 11th International Conference on Electrical Machines and Systems (ICEMS2008), Oct. 17-20, 2008, Wuhan, China, pp. 1721-1725.
[9] Xiaoyong Zhu, Ming Cheng, *Design, analysis and control of hybrid excited doubly salient stator-permanent-magnet motor*, Science China Tech Sci., Jan. 2010, Vol. 53, No. 1, pp. 188-199.
[10] Hai-yan Liu, Yi Wang, Jie Liu, et al., *Field-weakening control of induction motor for electric vehicles*, Electric Machines and Control, Vol. 9, No. 5 2005, pp. 452-460.
[11] Ruzhen Dou, Xuhui Wen, *Analysis of field weakening operation for the direct torque control of PMSM*, Proceedings of the CSEE, Vol. 25, No. 12, 2005, pp. 117-121(in Chinese).
[12] Lan Yan, Yikang He, Derong Yang, *The approach of the flux weakening operation study for a BLDCM with hybrid rotor structure*, Proceedings of the CSEE, 2003, Vol. 23, No. 11, 2003, pp. 155-159 (in Chinese).
[13] T. Humiston, P. Pillay, *Flux weakening operation of switched reluctance motors*, IEEE Power Engineering Society Winter Meeting, 2001, vol.3, pp. 1372 - 1377.

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