Models and Simulation of the Switched Reluctance Motor Drive System

Hao Chen* and Jin-Woo Ahn**

Abstract - The paper presents the component parts and their models of the Switched Reluctance motor drive system with the angle position-current chopping control and with the fixed angle pulse width modulation control. The calculation of the parameters and the simulated models based on the MATLAB SIMULINK software package are introduced by a four-phase 8/6 structure prototype with the four-phase asymmetric bridge power converter. The simulation of the prototype in the course of starting is made by the simulated models at the different control strategies and the different given rotor speed.

Keywords: switched reluctance, models, simulation, MATLAB

1. Introduction

The Switched Reluctance motor drive system could operate in a very wide speed range with high efficiency. There are no windings, no magnet and a brushless structure on the rotor, and there is only multi-phase centralized windings on the stator, those give rise to its simple and firm structure. It has good prospects for application, such as the electric drive device in coal mine [1][2], in family electrical equipment, in aircraft [3][4] and so on. It is necessary for the design and research of the drive system to set up the models and make the simulation. The dynamic simulation of the Switched Reluctance motor drive system is essential to analyze and study the drives. The mathematical models of the machine [5] and the mathematical models of the power converter [6] have been set up, respectively. The Switched Reluctance motor drive system is made up of the Switched Reluctance motor, the power converter and the controller. The models and the simulation of Switched Reluctance motor drive system should be done from the systematic point of view.

The Switched Reluctance motor drive system has the control parameters, such as the average phase winding supplied voltage, the peak value of phase current, the turn-on angle and the turn-off angle of main switches in the power converter, that could be used to control the output torque and the rotor speed. There are some variable speed control strategies, such as the angle position-current chopping control [7] and the fixed angle pulse width modulation (PWM) control [8]. In the angle position-current chopping control strategy, the current chopping control is used at the low speed ranges. The turn-on angle of the main switches in the power converter is fixed at 0^0 (In the rotor position, the phase inductance has the minimum value, and the axis of the rotor slot is aligned with that of the stator pole of an conducted phase), and the turn-off angle of the main switches in the power converter is fixed at θ m (In the rotor position, the phase inductance has the maximum value, and the axis of the rotor pole is aligned with that of the stator pole of an conducted phase). The phase current of the motor is measured and compared with the limit of the current chopping. If the phase current is bigger that the limit, the main switches in the power converter are turned off a certain time, then the main switches are turned on again, and so on. The output torque and the rotor speed are adjustable by regulating the limit of the current chopping. In the angle position-current chopping control strategy, the angle position control is applied at the high-speed ranges. The output torque and the rotor speed are variable by regulating the turn-on angle and the turn-off angle of the main switches in the power converter. In the fixed angle PWM control strategy, the turn-on angle and the turn-off angle of the main switches in the power converter are fixed, the triggering signals of the main switches are modulated by the PWM signal. The phase winding average voltage could be adjusted by regulating the duty ratio of the PWM signal so that the output torque and the rotor speed of the motor are adjustable by regulating the phase winding average voltage.

In the braking control of the Switched Reluctance motor drive system, the angle position control and the fixed angle PWM control [9] could be also adopted. The braking torque could be used to control by regulating the turn-on angle and the turn-off angle of the main switches in the power converter or by regulating the duty ratio of the PWM signal.

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At present, MATLAB is one of the most effective simulation tools for control system. The SIMULINK toolbox is the picture input and simulation tool of control system models that is provided by Math Works company [10]. It has two main functions, such as the simulation and the link. It could transfer the patterns in the warehouse directly or could create the new patterns, and it could set up the structural frame drawing of the control system by connecting the patterns, and then select the control parameters, finally, the simulation could be implemented. The SIMULINK toolbox is suitable for the simulation of the Switched Reluctance motor drive system. The paper introduces the founding models and simulation procedure of the drive system based on MATLAB software package.

2. Component Parts and Models

While the mechanical loss and the stray loss are neglected, there is the motional equation of the Switched Reluctance motor as follows,

$$T_{av} = J\frac{d\omega}{dt} + D\omega + T_L \tag{1}$$

Where, J is the sum of the inertia movement of the motor and the loads, D is the coefficient of the viscous-damping, ω is the rotor angular velocity, T_L is the torque of the loads that is the function of the angular velocity of the loads, T_{av} is the average electromagnetic torque of the motor. The model of the Switched Reluctance motor could be expressed as follow,

$$T_{av}(S) - T_L(S) = (JS + D)\omega \tag{2}$$

The relationship between the average electromagnetic torque of the motor and the control parameters based on the angle position control or the fixed angle PWM control could be expressed as follows [7],

$$T_{av} = K_m K_\theta \frac{U^2}{\omega^2} \tag{3}$$

$$K_m = m\frac{Z_r}{2\pi} \tag{4}$$

Where, Z_r is the number of the rotor poles, m is the phase number of the stator windings, U is the average phase winding supplied voltage, K_θ is the coefficient of the turn-on angle and the turn-off angle, which has the different value while the drive is operated at the different rotor speed range.

In the angle position control, the equation (3) and (4) could be expressed as follows,

$$T_{av} = K_m K_\theta \frac{U_s^2}{\omega^2} \tag{5}$$

Where, U_s is the DC supplied voltage of the power converter.

In the fixed angle PWM control, the equation (3) and (4) could be expressed as follows,

$$T_{av} = K_m K_1 \frac{U^2}{\omega^2} \tag{6}$$

Where, K_1 is a constant that is related to the fixed turn-on angle, the fixed turn-off angle, the structural parameters of the motor and the phase inductance. There is the voltage magnifying coefficient of the power converter with PWM signal chopping, " K_C ". The process of PWM chopping is regarded as the process of sampling the output signal of the rotor speed regulator. The zero step keeper could be equivalent to a little inertial unit.

The relationship between the average electromagnetic torque of the motor and the control parameters based on the current chopping control could be expressed as follows [7],

$$T_{av} = K_h I^2 \tag{7}$$

Where, I is the expected value of the phase current, K_h is a constant that has the relationship with the fixed turn-on angle, the fixed turn-off angle, the structural parameters of the motor, and the phase inductance, and K_m.

The rotor speed regulator is a PID regulator [11], the model is as follows,

$$D(S) = \frac{U_R}{U_g - U_f} = K_P(1 + \frac{K_I}{S} + K_D S) \tag{8}$$

Where, K_P is the proportional coefficient, K_I is the integral coefficient, K_D is the differential coefficient, U_g is the given voltage reference value of the rotor speed, and U_f is the feedback voltage value of the rotor speed.

The rotor position detector fixed on the end cover of the motor is the featured component of the Switched Reluctance motor drive that contributes to implement the rotor position closed-loop control and the rotor speed closed-loop control. The output signals of the rotor position give the feedback of the rotor speed that is implemented by a frequency/voltage transformer. The rotor speed feedback unit with a filter is equivalent to a small inertia unit, the model is as follows,

$$G_n(S) = \frac{K_n}{1 + T_n S} \tag{9}$$

Where, K_n is the feedback coefficient of the rotor speed, T_n is a time factor of the rotor speed feedback filter.

In order to equilibrate the delay of the rotor speed feedback filter, the rotor speed given filter with a time factor, T_g, is essential. The model is as follows,

$$G_g(S) = \frac{1}{1 + T_g S} \tag{10}$$

Fig.1 gives the model of the Switched Reluctance motor drive system with the angle position-current chopping control based on MATLAB SIMULINK toolbox. Where, the pattern " Step Fcn " sets up the given value of the expected phase current at the low speed ranges. The model of the drive with the current chopping control consists of the patterns, such as "Step Fcn", "Sum 1", "PID controller", "*" and "Gain 5". The pattern "Constant 2" gives the switch value of the rotor speed for switching the control strategies. "500" means that the switch value is 500 r/min. Switching the control strategies is implemented by the patterns "Switch" and "Switch 1". If the motor is operated below or at 500 r/min, the model of the drive with the current chopping control is put through, and the model of the drive with the angle position control is blocked. If the motor is operated over 500 r/min, the model of the drive with the angle position control is put through, and the model of the drive with the current chopping control is blocked. The pattern "MTALAB Fcn1" and the pattern "Gain2" give the characteristics of loads with the rotor angular velocity. The pattern "Given" sets up the given value of the rotor speed. The pattern "Delay" caused by the power converter has 0.006 second delay-coefficient. The patter "MATLAB Function-negative square" gives the function, $1/\omega^2$. The pattern " * " is a multiplier. "Clock" could be applied to control the operational time of the system. The pattern "Oscilloscope" could give the variation of the rotor speed of the drive. Fig.2 gives the model of the drive system with the fixed angle PWM control based on MATLAB SIMULINK toolbox. T is one period of the PWM signal.

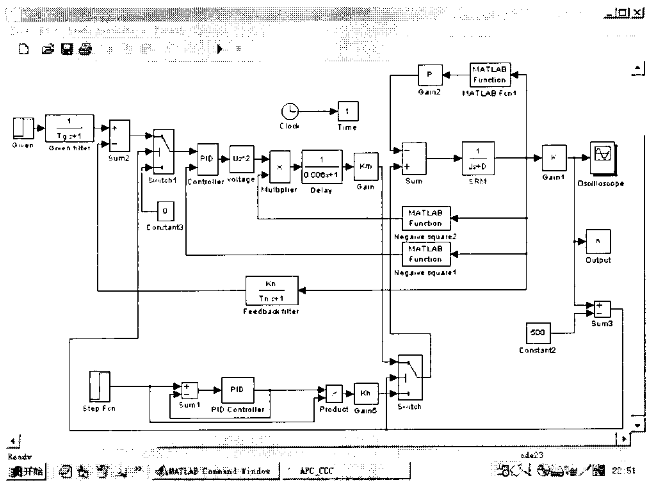


Fig. 1 Model of the drive with the angle position-current chopping control

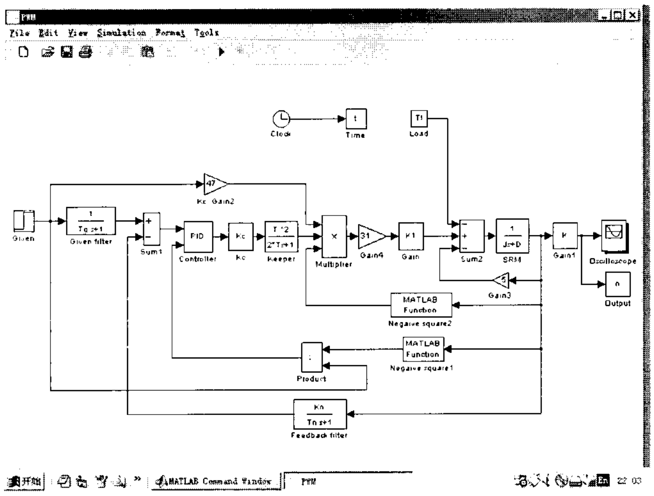


Fig. 2 Model of the drive with the fixed angle PWM control

3. Calculation of the Parameters

In the prototype, the Switched Reluctance motor is a four-phase 8/6 structure with the four-phase asymmetric bridge power converter, the DC bus voltage is *264 V*, the PWM signal frequency, f_l is *5.0 KHz*, the rated output is *250 W* while it is operated at the rated rotor speed, n, *1500 r/min*. The sum of the inertia movement of the motor and the loads is *0.05 N.m.s*^{2}.

The given voltage reference value of the rotor speed is regulated from 0 V to 10 V and the duty ratio of the PWM signal is varied from 0% to 88%, so the maximum value of the average phase winding supplied voltage is

$$U = 264 \times 88\% = 232.32 \quad \text{(V)} \tag{11}$$

The magnifying coefficient K_C is as follows,

$$K_C = \frac{232.32}{10} = 23.232 \qquad (12)$$

The period of the PWM signal is

$$T = \frac{1}{f} = \frac{1}{5.0\times10^3} = 0.2 \quad \text{(ms)} \qquad (13)$$

The rotor speed and the rotor angular velocity of the motor has the relationship as follows,

$$\omega = \frac{\pi n}{30} \qquad (14)$$

The rotor speed of the motor and the input frequency of the frequency/voltage transformer, f_{in}, has the relationship as follows,

$$n = 10 f_{in} \qquad (15)$$

The ratio of the frequency/voltage is

$$f_{in} / U_f = 40 \qquad (16)$$

From (14), (15) and (16), the feedback coefficient of the rotor speed is

$$K_n = 0.02387 \quad \text{(V.s/rad)} \qquad (17)$$

In the prototype, the time factor of the rotor speed feedback filter is

$$T_n = 0.11 \quad \text{(ms)} \qquad (18)$$

and the time factor of the rotor speed given filter is

$$T_g = 0.11 \quad \text{(ms)} \qquad (19)$$

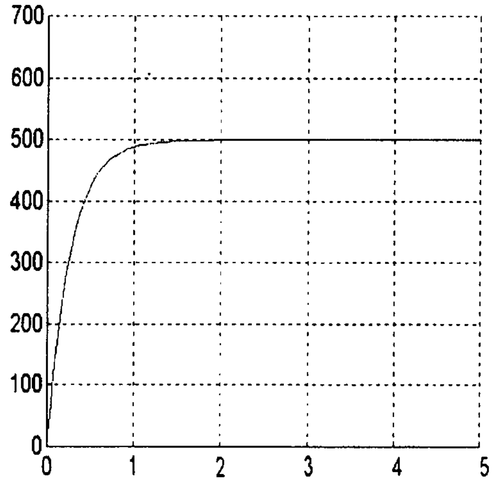
The coefficient of the viscous-damping is

$$D = 0.005 \quad \text{(N .m .s/rad)} \qquad (20)$$

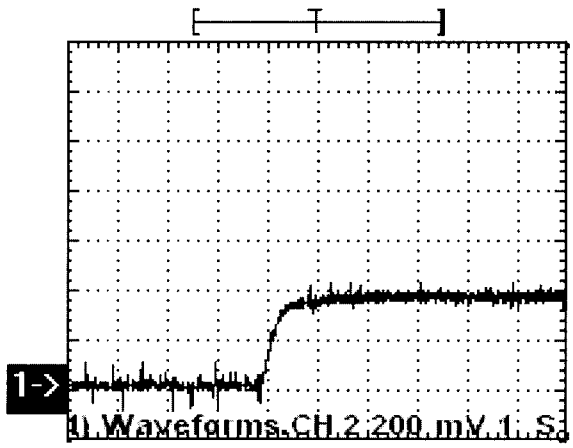
4. Simulation

The simulation of the Switched Reluctance motor drive prototype is made based on the above-mentioned MATLAB SIMULINK models. The step is *0.1 ms*, and the permissible error is *1.0* $\times$ *10*$^{-4}$.

In the angle position-current chopping control, Fig.3 gives the simulated rotor speed curve of the drive in the course of starting, while the given rotor speed is 500 r/min. Fig.4 gives the tested rotor speed curve of the drive at the same conditions.



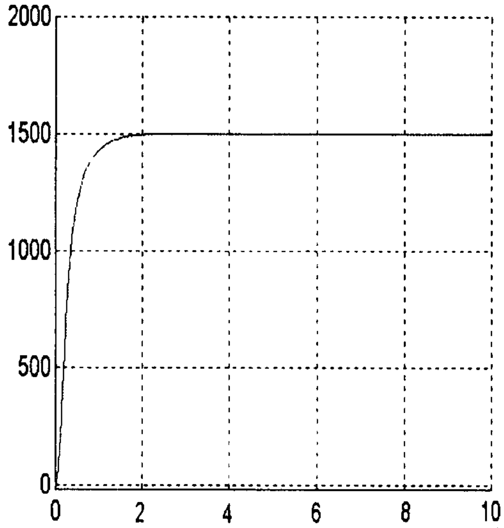
Abscissa: Time (s)
Ordinate: Rotor Speed (r/min)
Fig. 3 The simulated rotor speed curve of the drive system



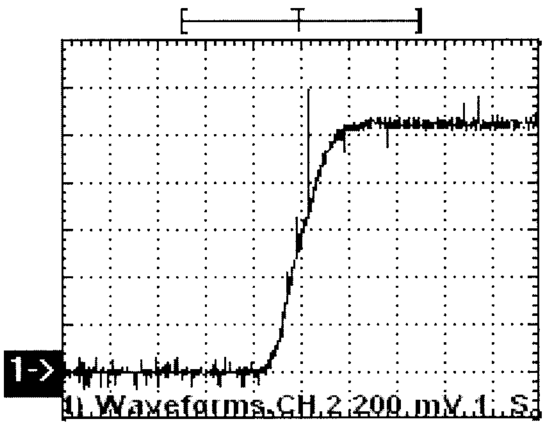
Scale: Abscissa: 1.0 s/div. Ordinate: 250 r/min /div.
Fig. 4 The tested rotor speed curve of the drive system

In the fixed angle PWM control, Fig.5 gives the simulated rotor speed curve of the drive in the course of starting, while the given rotor speed is 1500 r/min. Fig.6 gives the tested rotor speed curve of the drive in the same conditions.

It is shown that the simulated rotor speed curve of the drive at the same conditions tally with the tested rotor speed curve of the drive in the experiments.



Abscissa: Time (s)
Ordinate: Rotor Speed (r/min)
Fig. 5 The simulated rotor speed curve of the drive



Scale: Abscissa: 1.0 s/div. Ordinate: 288 r/min /div.
Fig. 6 The tested rotor speed curve of the drive system

5. Conclusions

The MATLAB SIMULINK software package contributes to set up the dynamic simulated models of the Switched Reluctance motor drive system precisely. Founding mathematical models of the Component Parts in the drive system determining the parameters in the models are the keys. MATLAB is one of the most effective simulation tools for control system at present. The SIMULINK toolbox is the picture input and simulation tool of control system models that is provided by Math Works company. It has two main functions, such as the simulation and the link. It could transfer the patterns in the warehouse directly or could create the new patterns, and it could set up the structural frame drawing of the control system by connecting the patterns, and then select the control parameters, finally, the simulation could be implemented. The SIMULINK toolbox is suitable for the dynamic simulation of the Switched Reluctance motor drives. The founding models and simulation procedure of the drive system with the angle position-current chopping control and with the fixed angle PWM control are given in the paper. The method and the procedure are suitable for the founding models and simulation of the Switched Reluctance motor drive system with other control strategies and with other construction.

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References

[1] P. Greenhough, "Switched reluctance variable speed drives-a focus on applications," *Mining Technology*, no.4, 1996, pp.107-110.
[2] H. Chen and G. Xie, "A switched reluctance motor drive system for storage battery electric vehicle in coal mine," in *Proceedings of the 5th IFAC Symposium on Low Cost Automation*, 1998, pp.95-99.
[3] S. R. MacMinn, "A very high speed switched-reluctance starter-generator for aircraft engine applications," in *Proceedings of NAECON*, 1989, pp.1758-1764.
[4] A. V. Radun, "High-power density switched reluctance motor drive for aerospace applications," *IEEE Trans. on IA*, vol.28, no.1, 1992, pp.113-119.
[5] M. Moallem, "Predicting the torque of a switched reluctance machine from its finite element field solution", *IEEE Trans. on Energy Conversion*, vol.5, no.4, pp.733-739, August 1990.
[6] H. Chen and G. Xie, "Design of the power converter for switched reluctance motor drives," *Journal of China University of Mining & Technology*, vol.27, no.2, 1998, pp.158-161.
[7] H. Chen and G. Xie, "Adjustable-speed control of

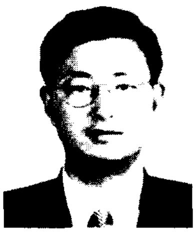
switched reluctance motor drive," in *Proceedings of the 8th International Power Electronics & Motion Control Conference*, vol.5, 1998, pp.56-59.

[8] H. Chen and G. Xie, "Theory and practice of PWM control for switched reluctance motors," *Journal of China University of Mining & Technology*, vol.26, no.3, 1997, pp.23-27.

[9] H. Chen and C. Zhang, "A new braking control strategy for switched reluctance motor drive," in *Proceedings of the 9th International Power Electronics & Motion Control Conference*, vol.5, 2000, pp.182-185.

[10] Math Works. *MATLAB Version 4.2 User's Guide*, 1995.

[11] H. Chen, W, Cheng, G. Xie, C. Zhang, "PID control of a switched reluctance motor drive with Intel 80C196KB microcomputer", in *Proceedings of IEEE Hong Kong Symposium on Robotics and Control*, vol.I, 1999, pp.304-307.



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