Research of Novel Modeling and Simulation Approach of Brushless DC Motor Control System

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***Abstract*—This work describes a novel modeling and simulation approach of brushless DC motor control system depended on analysis of it's mathematical model. The brushless DC motor ontology model, the voltage type inverter circuit model, the hysteresis current tracking comparative model and the PID speed controller model were constructed in the Simulink environment of Matlab. S-function was used in modeling to make the model simple and reflecting its mathematical model and the essence of running principle in the furthest way. Simulation results show that the modeling method is completely feasible, and simulating efficiency is high as the simulating model running quickly. The modeling approach provides a new idea for the model construction and has important application value for the research and design of brushless DC motor control system.**

Keywords-BLDCM;simulation;modeling;Matlab;hysteresis tracking

I. INTRODUCTION

Brushless DC Motor (BLDCM) overcomes many problems of the brush DC Motor and has been widely applied in various fields [1].The development of BLDCM control system requires reliable operation, excellent performance of control algorithm, low cost and short development cycle. Establishing effective and simple simulation model of BLDCM control system can test the control algorithm, effectively reduce the time and cost of the system development and has important value to research the control algorithm. MATLAB/Simulink is a modeling and simulation software widely used. In Simulink modeling environment, the modular modeling method conveniently, and the system function (S-function) model can direct reflect the mathematical model.

Many researchers pay attention to the study and test of control algorithm, and the research of establishing simple and efficient model reflecting the essence of the BLDCM control system is often ignored. Paper [2-4] introduced the control algorithm of BLDC control system and gave the results of simulation not involved the modeling methods in detail. In paper [5], the model of the BLDCM control system is not concise, especially the model of the inverter circuit which is not established on the mathematical model. This present work describes a novel modeling and simulation approach of BLDC control system depended on analysis of BLDC control system. The simple and efficient model is established mainly by the S-function according to the mathematical model in the Simulink environment of Matlab.

A. The structure of Brushless dc motor control system

The structure of BLDCM control system is shown in Fig.1. The double closed loop control system is used to adjusting the motor rotating speed and the current of the motor. The speed loop adopts PID adjustor and the current loop adopts hysteretic tracking comparison regulator. The main circuit of inverter adopts the voltage type circuits.

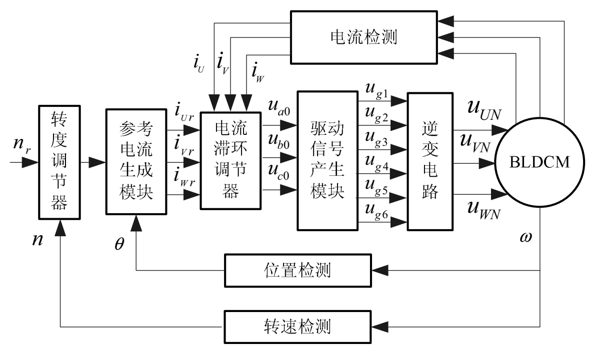

Fig.1 The structure of BLDCM control system

B. The mathematical model of Brushless DC motor [5]

Paper [5] introduced the ideal conditions of the BLDCM and the mathematical model of the BLCDM is established in these conditions. The back EMF and current of phase U is shown in Fig.2.

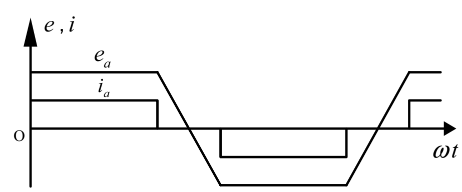

Fig.2 The back EMF and current of phase U

The voltage equation of BLDCM's three-phase winding voltages is:

$$\begin{bmatrix} u_U \\ u_V \\ u_W \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_U \\ i_V \\ i_W \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} p \begin{bmatrix} i_U \\ i_V \\ i_W \end{bmatrix} + \begin{bmatrix} e_U \\ e_V \\ e_W \end{bmatrix} . \quad (1)$$

Where u_U , u_V and u_W is phase voltages of the three-phase stator winding (V); i_U , i_V and i_W is phase currents of the three-phase stator winding (A); e_U , e_V and e_W is the back EMF (V); R is the Phase resistance (Ω); L is the Phase inductance (H); the mutual inductance of the three phase winding is M (H); $p = d/dt$,is the differential operator. The relationship of three phase current is $i_U + i_V + i_W = 0$. The torque generated by the three phase is

$$T_e = (1/\omega)(e_U i_U + e_V i_V + e_W i_W) \ . \quad (2)$$

The motion equation of the BLDCM is

$$T_e - T_L - B\omega = J(d\omega / dt) \, . \quad (3)$$

Where T_e = the electromagnetic torque (N · m); T_L = the load torque (N · m); B = the Damping coefficient (N · m · s/rad); ω = the rotation angular velocity of motor (rad/s); J = the inertia moment of motor (kg · m^2).

C. *The mathematical model of the inverter circuit*

Fig.3 shows the voltage type inverter circuit of the control system. Each phase has two bridge arms, and each bridge arm has one IGBT paralleled one fly-wheel diode inversely. The drive signals of the two arms in the same phase are complementary. Three phases U, V and W are similar, and just has the difference of 120 electrical degrees.

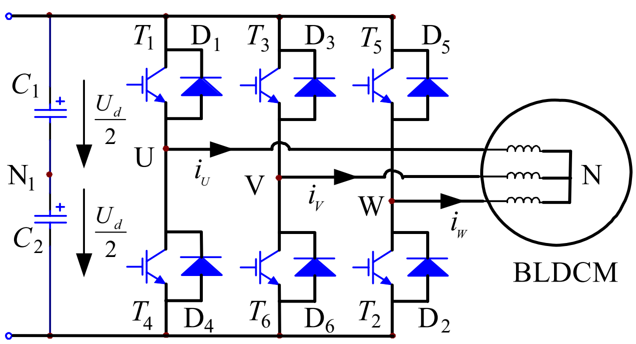

Fig.3 the voltage type inverter circuit

Phase U is taken for example to be analyzed. When the upper arm of phase U is opened, in the other word, the current flows through T_1 or D_1, the voltage between the point U and the point N_1 is $u_{UN1} = U_d / 2$. When the nether arm of phase U is opened, the voltage between the point U and the point N_1 is $u_{UN1} = -U_d / 2$. The voltages of the three phases are

$$u_{UN} = u_{UN1} - u_{NN1} \quad (4)$$

$$u_{VN} = u_{VN1} - u_{NN1} \quad (5)$$

$$u_{WN} = u_{WN1} - u_{NN1} \, . \quad (6)$$

From (4)-(6), it can be shown that

$$u_{NN1} = (1/3)(u_{UN1} + u_{VN1} + u_{WN1}) - (1/3)(u_{UN} + u_{VN} + u_{WN}) \ . \quad (7)$$

For the three-phase load is symmetric, it can be shown that $u_{UN} + u_{VN} + u_{WN} = 0$. Hence, the voltage between the point N and the point N_1 is

$$u_{NN1} = (1/3)(u_{UN1} + u_{VN1} + u_{WN1}) \, . \quad (8)$$

The model of the voltage type inverter circuit is proposed according to above analysis.

II. THE ESTABLISHMENT OF BLDCM CONTROL SYSTEM BASED ON SIMULINK

The structure of BLDCM control system is shown in Fig.1. The BLDCM ontology module, the voltage type inverter circuit module, the Drive signal generated module, the hysteretic current tracking comparative regulator module, the reference current generated module and speed control module are mainly considered in modeling.

A. *The BLDCM ontology module*

Fig.4 shows the organization chart of the BLDCM ontology module which simulates functions of BLDCM.

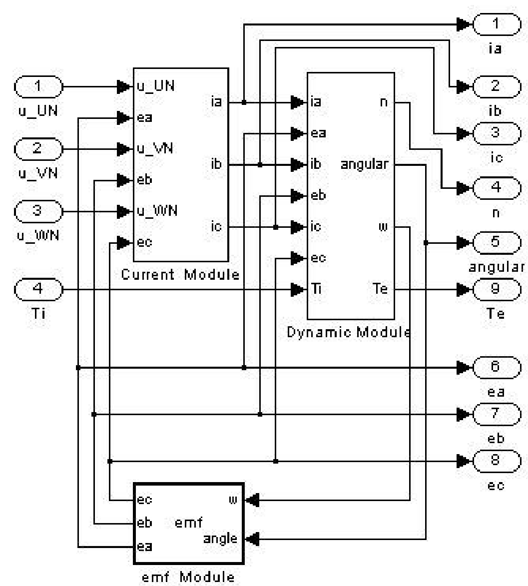

Fig.4 The structure of BLDCM control system

The BLDCM ontology module consists of the back EMF calculation module, the Current calculation module and the dynamics module.

The input signal of the back EMF calculation module is the position signal and the rotation angular velocity of the rotor. The output signal of the back EMF calculation module is the EMF of three phases. This module is completed by S-function, and table 1 lists the relationship of inputs and output for one cycle [5].

The structure of current calculation module is shown in Fig.5 [5]. The inputs of the module are u_{UN} , u_{VN} and u_{WN} ,which are the outputs of the voltage type inverter circuit, and e_U , e_V , e_W ,which are the outputs of the EMF calculation module. The outputs of the module are i_U , i_V and i_W ,which are the current of the three-phase winding. R , L and M are the parameters of the module.

The structure of dynamic module is shown in Fig.6. The current and the back EMF of the three-phase winding are the inputs of the module. The outputs of the module are n , T_e , ω and $angular$. The parameter of the module is rotor-pole pairs p. Where n = rotating speed of the motor (r · min); $angular$ = angular rotation (rad).

TABLE I. THE RELATIONSHIP OF INPUTS AND OUTPUT FOR ONE CYCLE OF THE BACK EMF CALCULATION MODULE

The position signal of the rotor	The back EMF of the stator windings		
	e_U	e_V	e_W
$0\sim\pi/3$	$k*\omega$	$-k*\omega$	$k*\omega*((-Pos)/(\pi/6)+1)$
$\pi/3\sim2\pi/3$	$k*\omega$	$k*\omega*((Pos-\pi/3)/(\pi/6)-1)$	$-k*\omega$
$2\pi/3\sim\pi$	$k*\omega*((2\pi/3-Pos)/(\pi/6)+1)$	$k*\omega$	$-k*\omega$
$\pi\sim4\pi/3$	$-k*\omega$	$k*\omega$	$k*\omega*((Pos-\pi)/(\pi/6)-1)$
$4\pi/3\sim5\pi/3$	$-k*\omega$	$k*\omega*((4\pi/3-Pos)/(\pi/6)+1)$	$k*\omega$
$5\pi/3\sim2\pi$	$k*\omega*((Pos-5\pi/3)/(\pi/6)-1)$	$-k*\omega$	$k*\omega$

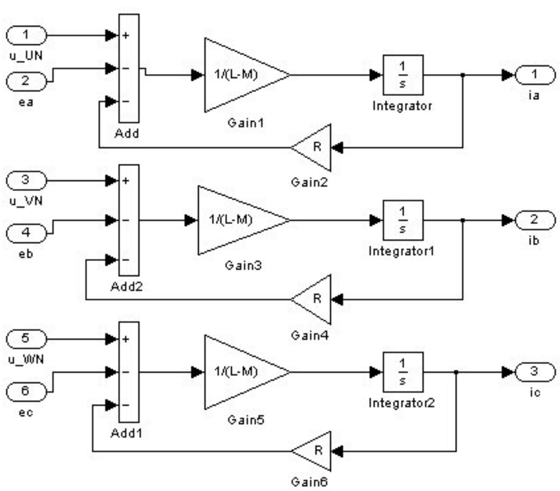

Fig.5 The structure of the current calculation module

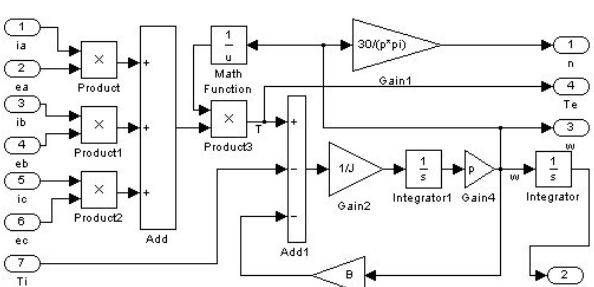

Fig.6 The structure of the dynamic module

B. The Speed regulating module [6-8]

The speed regulating module adopts discrete PID algorithm. The inputs of the module are n^* and n . n^* is the reference signal (r · min) and n is the feedback signal of the rotating speed. The output signal has negative saturated limiting value and positive saturated limiting value. The saturated limiting value is the maximum current value. Fig.7 is the structure of the speed control module.

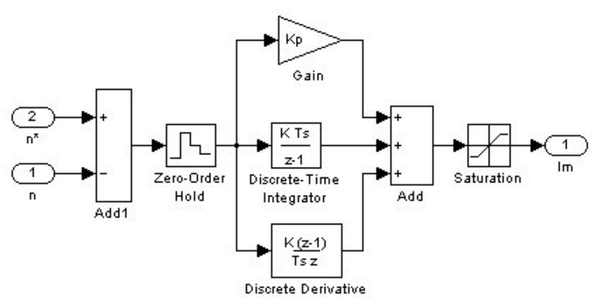

Fig.7 The structure of the speed control module

C. The reference current generating module

The reference current generating module has two inputs. One is the output of the speed control module, I_m , and the other is the angular displacement signal of the rotor, $angular$ .The output of the module is the current of the three-phase winding. The position signal of the rotor, Pos (rad), is calculating as following

$$Pos = angular - floor(angular/2/\pi)*2\pi . \qquad (9)$$

Table 2 lists the relationship of Pos and the current of the three-phase winding.

TABLE II. THE RELATIONSHIP OF INPUTS AND OUTPUTS OF THE REFERENCE CURRENT GENERATING MODULE

Pos	the current of the three-phase winding		
	i_{ar}	i_{br}	i_{cr}
$0\sim\pi/3$	I_m	$-I_m$	0
$\pi/3\sim 2\pi/3$	I_m	0	$-I_m$
$2\pi/3\sim\pi$	0	I_m	$-I_m$
$\pi\sim 4\pi/3$	$-I_m$	I_m	0
$4\pi/3\sim 5\pi/3$	$-I_m$	0	I_m
$5\pi/3\sim 2\pi$	0	$-I_m$	I_m

D. the current hysteresis tracking comparison regulator and the drive signal generating module

The current hysteretic tracking comparison regulator and the drive signal generating module controlling the power devices of the inverter circuit makes the actual three-phase current tracks the reference three-phase current through the current hysteretic tracking control technology. So the three phases each has a tracking comparison regulator. The inputs of the module are the reference currents of three phases, and the output signals are outputs of tracking comparison regulators of three phases. With phase U for example, when the value of the reference current i_{Ur} subtracting the actual current i_U goes to the positive lag edge, the regulator output high level, and the IGBT on the upper bridge arm of Phase U is driven to open, the IGBT on the nether bridge arm of Phase U is driven to close. The current flows past the upper bridge arm of phase U. Thus we have $u_{UN1} = U_d / 2$. So the actual current of the phase U goes after the reference current of phase U. Since the upper bridge arm's drive signal and the nether bridge arm's drive signal of one phase are opposite in phase, the logic operator is used to generate the inverse signal. Fig.8 is the structure of the current hysteretic tracking comparison regulator and the drive signal generating module.

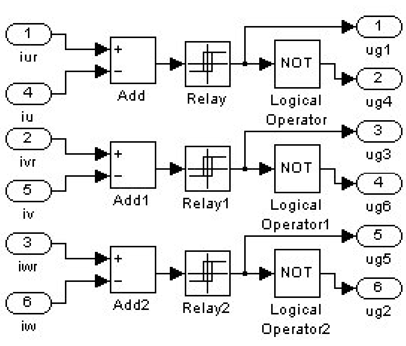

Fig.8 The structure of the current hysteretic tracking comparison regulator and the drive signal generating module

E. the voltage type inverter module

The voltage type inverter module can be designed depended on the analysis of it's mathematical model. The module is established using the S-function combined with the Basic function module. The inputs of the S-function are the drive signals of the six IGBT. The parameters of the S-function is the voltage of the inverter. The function of the S-function is: firstly, calculates the voltages u_{UN1} , u_{VN1} and u_{WN1} according to the drive signals of the six IGBT, and then calculates the three-phase voltage u_{UN} , u_{VN} and u_{WN} which are the phase voltages connected to the BLDCM module. The DC voltage is 200 V. The S-function is expressed as:

```
function[u_UN1,u_VN1,u_WN1]=fuc(ug1,ug4,ug3,ug6,ug5,ug2)
if(ug1==1)&&(ug2==1)
   u_UN1=100;u_VN1=0;u_WN1=-100;
elseif (ug1==1)&&(ug6==1)
   u_UN1=100;u_VN1=-100;u_WN1=0;
elseif (ug3==1)&&(ug4==1)
   u_UN1=-100;u_VN1=100;u_WN1=0;
elseif (ug3==1)&&(ug2==1)
   u_UN1=0;u_VN1=100;u_WN1=-100;
elseif (ug5==1)&&(ug4==1)
   u_UN1=-100;u_VN1=0;u_WN1=100;
elseif (ug5==1)&&(ug6==1)
   u_UN1=0;u_VN1=-100;u_WN1=100;
else
  u_UN1=0;u_VN1=0;u_WN1=0;
end.
```

III. RESULTS AND DISCUSSION

The module of BLDCM rotating speed and current double closed loop control systems which is established in the environment of Simulink is simulated in this work. The simulated parameters are set as follows: DC voltage 200V, moment of inertia of system J =0.005 kg · m^2,damp coefficient B =0.0008 N · m · s/rad, rating rotating speed of BLDCM n =1000r/min, number of pole pairs p =1, phase resistance of stator winding $R = 0.5\Omega$, self inductance of phase winding L=0.05H, mutual inductance of phase winding M =0.01H. The controller parameters of double closed loop are set as follow: K_p = 10, K_i = 0.01, K_d =0.03, saturation bound of output ± 20, lag loop width of current loop 0.2A, sampling period 0.001s. The system is started in the state of no load. After it is in steady state at 0.4s, the system is loaded 3 N · m, and at 1s, the load abruptly becomes 1 N · m. The simulated result of rotating speed, three-phase current of three-phase winding and electromagnetism torque are in the Fig.9 ~ Fig.11. The speed curve shows the high tracking speed and small overshoot and the effectiveness of the proposed algorithm. The phase current curve is square wave with positive and negative plats of 120 electrical degrees. When the motor is started, its current is limited to a set value.

This can guarantee the speediness of start-up. The fluctuation of the electromagnetic torque is small, except when the load torque appears mutations. The results of simulation show the novel modeling and simulation approach of BLDCM control system is correct and available.

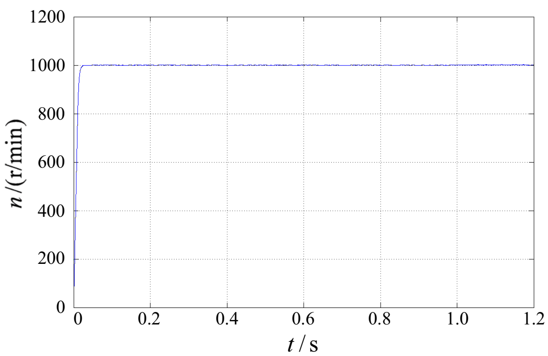

Fig.9 The response curve of rotating speed

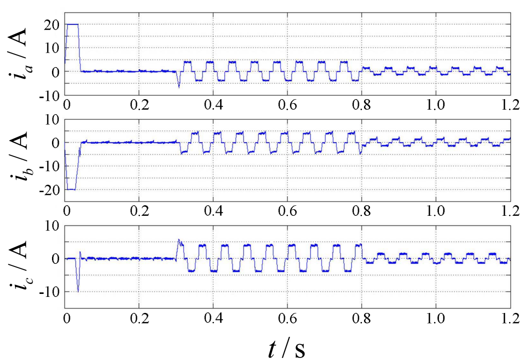

Fig.10 The curve of three-phase current

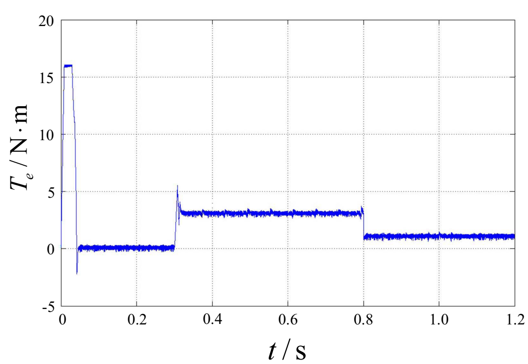

Fig.11 The curve of electromagnetic torque

IV. CONCLUSION

In this work, through analyzing the mathematical model of BLDCM control system, one novel modeling and simulation approach of BLDCM control system which is based on Matlab is put forward, depended on the analysis of mathematical model of the system. The double closed loop control system is used to adjusting the motor rotating speed and the current of the motor. The speed loop adopts PID adjustor and the current loop adopts hysteretic tracking comparison regulator. The main circuit of inverter adopts the voltage type circuits. In the environment of Simulink, all parts of the model are created by using S-function. The model is simple and can reflect essence of mathematic model and running principle in the furthest way. The result of simulation can indicate that the modeling method is reasonable and the simulating running speed is very quick and simulating efficiency is high. The modeling method can put forward a new thinking for modeling of BLDCM and can provide very important value for simulating research and design application of BLDCM control system.

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