TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol.12, No.1, January 2014, pp. 254 ~ 260
DOI: http://dx.doi.org/10.11591/telkomnika.v12i1.3964

Study on Current Sensorless Vector Control Method for Electric Vehicle Drive Motor

Jing Lian, Yafu Zhou, Jing Chang, Linhui Li*, Xiaoyong Shen
School of Automotive Engineering, Dalian University of Technology, Dalian, PR China
Chuangxinyuan Highrise No.D0210, Linggong Road No.2, Ganjingzi Borough
Dalian, 116024, China; Ph./Fax:+86-411-84706475/+86-411-81907253
*Corresponding author, e-mail: 37132923@qq.com

Abstract

With the aggravation of environment pollution and the reduction of petroleum resources, the development of electric vehicle (EV) draws more and more people's attention. In the EV research field, that seeking for a high efficient and reliable motor control method that suits the operating conditions and characteristics of the vehicle drive motor has become one of the key techniques that need to be broken through urgently. Owing to the problems that the efficient work area is narrow and it leads to over-current phenomenon when traditional motor vector control method is applied to vehicle drive motor, this paper presents a current sensorless vector control technique for electric vehicle drive motor. According to motor speed and command torque which is gained from the speed loop control, this method directly controls the magnitude and phase angle of voltage vector to realize the orientation control of the magnetic field and then achieve the purpose of controlling the motor torque and speed. The feasibility and effectiveness of this method are verified by simulation results and bench test. Moreover, this method can not only improve the efficient work area, but also increase the reliability of motor control system. At the same time, it overcomes the dependence on the current sensor, circumvents the over-current defect caused by traditional motor vector control approach and reduces its cost. So it is a suitable and efficient control method for electric vehicle drive motor.

Keywords: *Electric vehicle, Drive motor control, Current sensorless control*

1. Introduction

With the aggravation of environment pollution and the depletion of petroleum resources, global car industry is forced to seek new energy-saving and environmentally friendly type of vehicle dynamic system constantly [1], which accelerates the research process of the electric vehicle techniques [2] [3]. Motor as well as its control technique is one of the key techniques of EV[4], which directly influences the dynamic performance, fuel economy and emission target of the whole vehicle [5] [6]. Vector control is widely used in automotive drive motor [7], which is controlled by regulating excitation and torque magnetic field through the PI current feedback control [8]. Although this method succeeds in the traditional industrial control, it is difficult to meet the demand of auto electric motor. For example, the integral action of I control component exists IGBT(Insulated Gate Bipolar Transistor) over-current phenomenon, which will shorten the IGBT's life and reduce the safety and reliability of the motor controller [9] so that the ability of dynamic system fast tracing the control target will be poor. Moreover, sole P control has significant limitations and its control effect is unsatisfactory. Besides, the measurement error of the current sensor is relatively obvious when small current works, which makes motor control performance poor and inefficient [10]. And the motor will get out of control once the current sensor goes wrong suddenly. Especially it will be very dangerous if the vehicle is in high-speed state.

Since the stator phase voltage exerts external excitation directly to motor, so the phase current is ultimately changed by adjusting the phase voltage for vector control, and then it controls the Magnetic Motive Force (MMF) and space magnetic field inside the motor. So in this paper, based on Permanent Magnet Synchronous Motor (PMSM) [11] [12], we propose a current sensorless vector control method for electric vehicle drive motor and finds out the optimal parameter matching of each set-point, generates three-dimensional MAP when the motor works in different operating modes by making bench calibration of motor. When the motor

Received June 21, 2013; Revised August 11, 2013; Accepted September 16, 2013

is under control, based on the optimal parameters in the MAP, we can refer to the three-dimensional MAP stored in motor control program so as to obtain the optimal demand voltage vector magnitude and phase angle, and take the space voltage vector as a control object straightly to realize the high efficient and reliable control of the motor. This method cancels the current loop in the vector control, breaks through the dependence on the current sensor in the traditional vector control and reduces the cost. At the same time it avoids not only the over-current defects caused by PI closed-loop control, but also the dependence on the current measure. In this way, it can ensure the ability of the vehicle normal driving and improve the reliability of the vehicle motor control system when the current sensor goes wrong suddenly [13].

2. Drive Motor Control System

The basic idea of current sensorless vector control method for electric vehicle drive motor proposed in this paper is to obtain command torque through the speed loop control, and then according to motor speed and command torque, this method directly controls the magnitude and phase angle of voltage vector to realize the orientation control of the magnetic field and then achieve the purpose of controlling the motor torque and speed. Schematic diagram of drive motor control system is shown in the Figure 1. It includes Motor speed and angular position sensor, speed-loop control module, motor-control MAP query module, space voltage vector PWM module, inverter module, power battery pack and PMSM. (n^* means command speed, n means actual speed, T^* means torque instruction value, U^* means voltage amplitude instruction value, θ^* means voltage phase instruction value, φ means rotor mechanical angle).

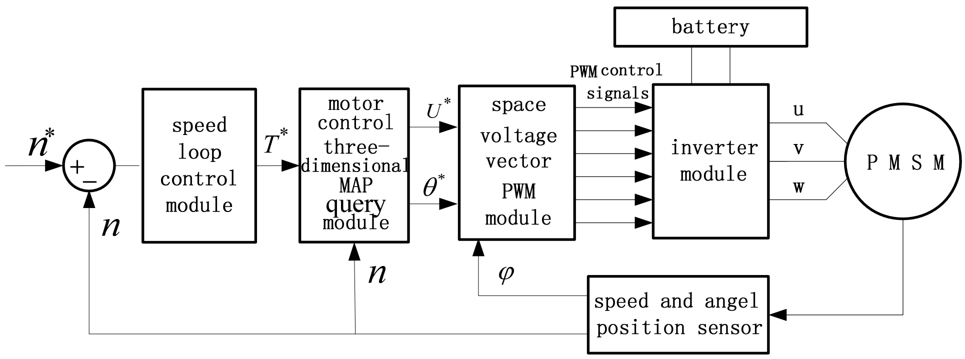

Figure 1. Schematic diagram of drive motor control system

In order to achieve current sensorless vector control method for EV drive motor, firstly we need to conduct the motor calibration test, forming the motor operating point control MAP saved in the motor control program in the form of table. When the motor is under control, the command torque values are first determined by the speed-loop control module according to the deviation between the command speed and the actual speed. Then the voltage amplitude and phase command are given out by motor control three-dimensional MAP query module inquiring MAP and calculated by the surface difference according to command torque and motor speed. Then six routes' PWM control signals are calculated by space voltage vector PWM module according to the amplitude and phase of the voltage as well as rotor mechanical angle, making the inverter module generate three-phase AC voltage to control motor. The specific control procedures of current sensorless vector control method are as follows:

2.1. The Calibration Process of Motor Control Three-dimensional MAP

Step one, in the motor bench test, select a series of operating points on the n–T graph of the motor, make marks every Δn from n_{min} to n_{max} of the motor speed and every ΔT from T_{min} to T_{max} of the motor torque as the calibration points of the motor control three-dimensional MAP.

Step two, at each calibration point of motor control three-dimensional MAP, adjust voltage vector value U and phase angle θ to satisfy the demand of the motor speed n and torque T. Select a group of U and θ that make the three-phase current I minimum as the optimal value of this calibration point in the motor control three-dimensional MAP.

Step three, finish all the optimal values of calibration points in the motor control three-dimensional MAP, construct a piece of optimal motor control three-dimensional MAP and save it in the motor control program in the form of table.

2.2. The Process of Vector Control

Step one, motor control three-dimensional MAP query module inquires motor control three-dimensional MAP according to target torque T^* and motor speed n^*, determines the triangular operating area of T^* and n^* in the MAP and obtains the motor torque T_i, the motor speed n_i, the optimal voltage vector value U_i and the optimal phase angle value θ_i (i=1,2,3). As Figure 2 shows.

Step two, the surface difference will be calculated according to T^*, n^* and T_i, n_i, U_i, θ_i gained in the vertex of the triangle so as to get the demand optimal voltage vector U^* and optimal phase angle θ^* where the motor works at the torque of T^* and the speed of n^*. As is shown in Figure 2.

Step three, according to θ^* and φ^*, space voltage vector PWM module gains the vector angle $\theta^*+\varphi^*+\pi/2$ where voltage vector is calculated in α−β UVW, as Figure 3 shows. Then six routes' PWM control signals are calculated through U^* and $\theta^*+\varphi^*+\pi/2$, controlling the inverter module to generate three-phase AC voltage to control the operation of the motor.

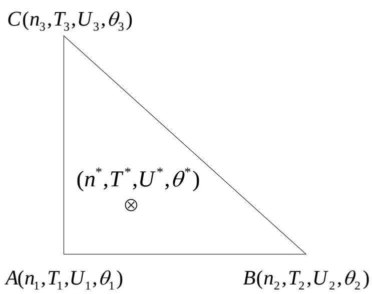

Figure 2. Triangular operating area figure of three-dimensional MAP

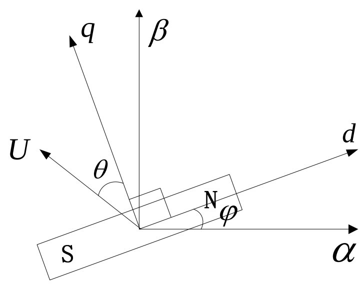

Figure 3. Vector control coordinate system

3. Simulation Analysis

3.1. Simulation Model

This paper builds the simulation model of PMSM current sensorless control system under the Simulink simulation environment, as is shown in Figure 4. This model mainly includes PMSM module, MAP query module, inverter module, space voltage vector PWM module, rotating speed and rotor angle position detection module etc. Among these, the function of the MAP query module is to provide voltage amplitude value and phase value according to command torque and motor speed. Space voltage vector PWM module determines voltage amplitude and phase command as well as the rotor mechanical position according to MAP query module, generates six routes' PWM signals, controls the on-off of the inverter's up or down bridge arm, and then forms circular rotating field to control the operating of the motor.

3.2. Simulation Experiment

The parameters of the PMSM in this simulation model are: the rated speed 3000rpm, the pole number 4, the stator phase winding resistance 2.875 Ohm, the stator d, q axis inductance 0.85mH, permanent magnet flux 0.175Wb, moment of inertia 0.008 kg • m^2. The parameters of the PI controller are: KP=0.55, KI=32. When the system goes into steady state after starting with no load,if we exert TL=20N•m suddenly at the time of 0.03s, we can get the simulation curve of the system rotating speed, torque and three-phase stator current, as is shown in Figure 5 to Figure 7. It can be seen from the simulation waveform, under reference speed 3000rpm, the system responds quickly and steady, the waveform of the phase current is relatively ideal. When the system runs smoothly with no load, the friction torque and the motor loss of the system can be ignored, so the mean value of the magnetic torque at this moment is zero. At the time of 0.03s, the speed drops abruptly with suddenly load, but it can return to the poised state rapidly. There is no offset when it runs steady.

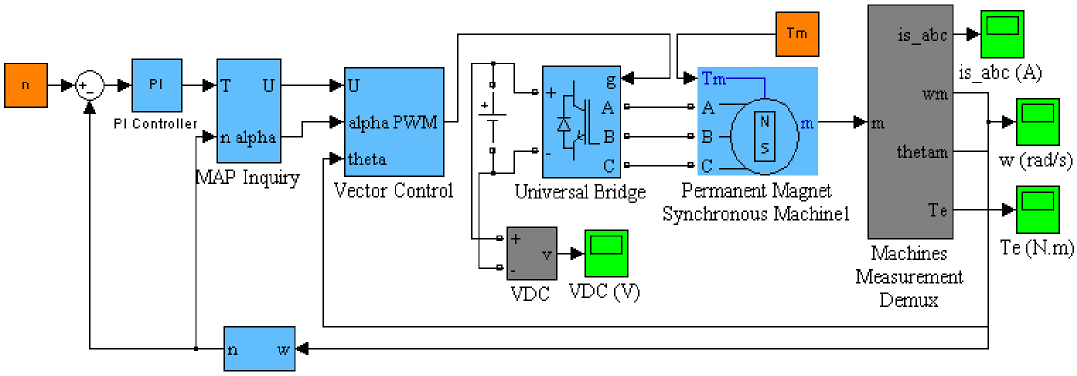

Figure 4. Simulation model

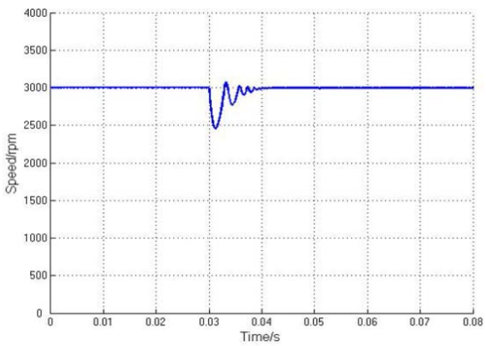

Figure 5. Speed curve

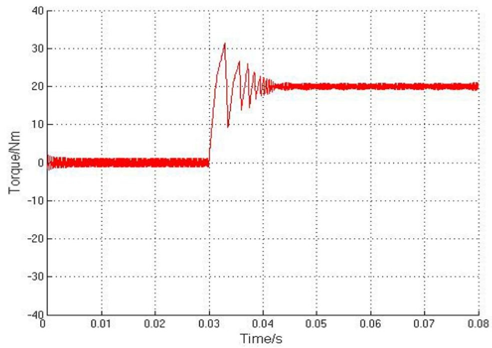

Figure 6. Torque curve

4. Test Bench

4.1. Build the Experimental Platform of the Drive Motor

In order to verify the feasibility of the current sensorless control method proposed above for vehicle drive motor further, and study the control and calibration method of the motor intensively, we build this experimental platform of drive motor. The experimental platform system is shown in Figure 8, in which 1 is upper computer, 2 is motor controller which is used for measure, 3 is power analyzer, 4 is battery pack, 5 is on-line battery charger, 6 is dynamometer controller, 7 is eddy current dynamometer, 8 is working stand, 9 is the measured motor, 10 is the water-cooling system, 11 is CAN communication transceiver. Based on this experimental platform, we can perform calibration test, control method test and various performance tests of the motor system. Figure 9 is the experimental platform to build the physical map.

4.2. Experimental Results and Analysis

Based on the drive motor experimental platform built in the laboratory, we conduct motor calibration experiment and efficiency experiment.

4.2.1. Motor Calibration Experiment

The motor body parameters have an important impact on the control effects, but the calculating parameter is always diverging from the actual one when the motor is designed. It is mainly because of the fact that the material parameter is inaccurate when the motor is designed, meanwhile, in the process of calculation, we ignore many secondary causes such as the environment and temperature change when we conduct the test, the machining accuracy influence and the parameter of the material property change when it used in this working condition. So high-performance motor control must calibrate the motor in different working conditions, and then form the motor control MAP.

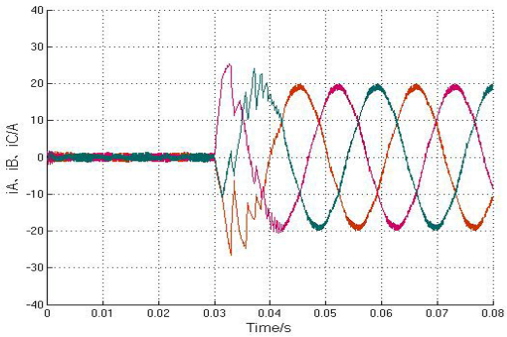

Figure 7. Phase current curve

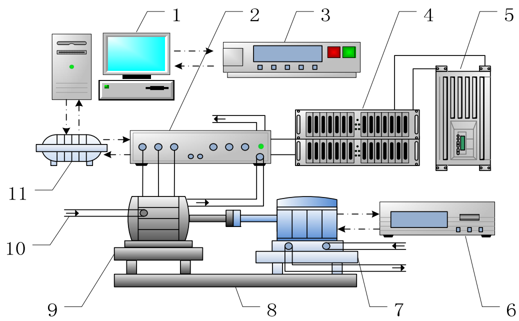

Figure 8. Drive motor experiment platform system

According to the current sensorless vector control method for EV drive motor in this paper, select a series of working points in the motor n-T figure as the calibration points of the motor control three-dimensional MAP. Table 1 is the experimental data calibrated at the 3072rpm, 64Nm working point of the motor. It is can be seen from the data that the motor efficiency is different corresponding to different voltage amplitude and phase for all the working points of the same motor, which isn't considered in the traditional motor control method. If you select the operating point to maximize efficiency of the voltage amplitude and phase angle of motor control to form the motor control MAP, and then control the motor based on this MAP, you are able to make the best use of the motor and improve the efficiency of the motor.

Table 1. Motor calibration experiment data

No.	Speed/rpm	Torque/Nm	Voltage phase /°	Voltage amplitude /V	Efficiency
1	3072	64	37	230	0.89
2	3072	64	38	226	0.90
3	3072	64	40	222	0.91
4	3072	64	41	218	0.90
5	3072	64	42	214	0.89
6	3072	64	43	210	0.89
7	3072	64	44	206	0.88

4.2.2. Motor Efficiency Test

In the drive motor experimental platform, we perform the motor working efficiency test based on the MAP formed in the calibration test. By measuring the motor input voltage and current as well as the motor output speed and torque at each motor's operating points in the n-T figure, we can figure out the motor working efficiency at each operating point. The three-dimensional surface of the motor working efficiency is shown in Figure 10.

As is shown in the figure, the motor high-efficient work area has been expanded with the maximum efficiency reaching to 94%. It can satisfy the hybrid electrical vehicle drive motor's demand for maintaining high efficiency in the larger torque scope and greater speed range.

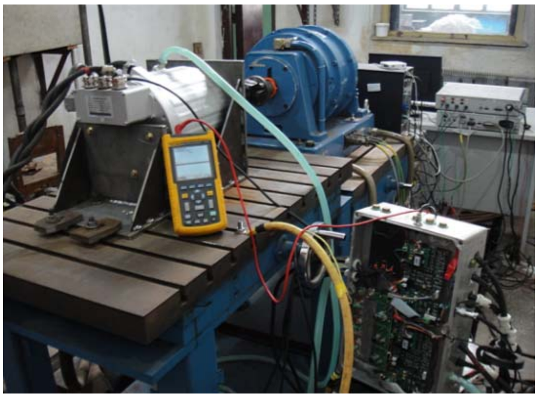

Figure 9. Picture of drive motor experiment platform

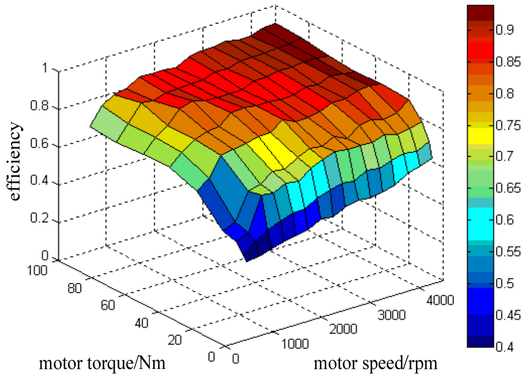

Figure 10. Motor efficiency graph

5. Conclusion

In the traditional vector control method, it's very hard for the feedback loop PI control to satisfy the demand for the quick response, and it will cause over-current phenomenon, shorten the IGBT's life in motor control. Aimed at overcoming the mentioned above shortcomings, this paper proposes a current sensorless vector control method for EV drive motor. The optimal demand voltage vector value and phase angle are obtained by inquiring the motor control three-dimensional MAP stored in the motor control program to conduct feed-forward vector control. This method responds quickly, avoids over-current phenomenon, eliminates the dependence on the current measurement, circumvents the problem of being unable to control under the condition of current sensor's malfunction and reduces the cost. It not only improves the control performance, but also increases the reliability of the system at the same time.

Acknowledgment

This project is supported by the National Natural Science Foundation of China (Grant No. 51107006, 61203171), China Postdoctoral Science Foundation (Grant No. 2012M510799, 2013T60278) and the Fundamental Research Funds for the Central Universities (Grant No. DUT12JS03, DUT12JR04).

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