Original Research Paper

Volume-9 | Issue-7 | July - 2019 | PRINT ISSN No. 2249 - 555X

Engineering

DIRECT TORQUE CONTROL OF PMSM IN EV AND REDUCTION OF TORQUE RIPPLE USING INTEGRAL CONTROL

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ABSTRACT This paper presents the Direct Torque Control (DTC) of Permanent Magnet Synchronous Motor (PMSM) and the reduction of ripple content in the output torque by using Integral control action in an Electric Vehicle (EV). The PMSM is a strongly coupled nonlinear system, application of DTC to PMSM motor drives offers a fast and accurate control. The basic DTC scheme may bring large amount of ripples in the output torque. This torque ripple can bring problems such as speed fluctuation and acoustic noise. In order to reduce the ripple content in the output torque an Integral control action is being introduced. The results showed that by using an integral control the ripple content in the output torque can be reduced.

KEYWORDS : direct torque control; PMSM; torque ripple; Integral control action

INTRODUCTION

The Permanent magnet synchronous motors (PMSM) are commonly used in industrial, Electric Vehicle (EV) and robotic applications due to their compact structure with small size and weight, high torque to inertia ratio, high efficiency, wide speed range, low noise and robust operations. The PMSM uses permanent magnet embedded in steel rotor to create a constant magnetic field. The stator carries windings connected to an AC supply to produce a rotating magnetic field. At synchronous speed the rotor poles lock to the rotating magnetic field. The PMSM is very much similar to the brushless DC motors. The PMSM is a non-linear electromechanical energy conversion device hence it is susceptible to the influence of uncertainties such as motor parameter variation and load disturbance. One of the major problem associated with the PMSM is the ripple content present in the torque output. The torque ripple of the PMSM can cause problems such as speed fluctuation, resonance and acoustic noise which may affect the device's reliability and accuracy.

In order to improve the steady state and dynamic performance of the PMSM drive methods like field oriented control (FOC) with pulse width modulation are used. The major drawback of this scheme is the limited bandwidth which leads to an unsatisfactory control performance during transient state. Thus a direct torque control strategy is proposed to improve the dynamic performance of ac machines that need fast transient responses. The basic principle of DTC scheme is to select the optimal stator voltage vectors based on the error sign between the torque and the estimated stator flux linkage values. But even after applying DTC torque ripples can be observed, this can eliminated by using an integral control action.

ELECTRIC VEHICLE (EV)

An electric vehicle also called an EV, uses one or more electric motor for propulsion. The first EV was built in 1834 by Thomas Davenport. Figure 1 shows the major electrical components of an EV.

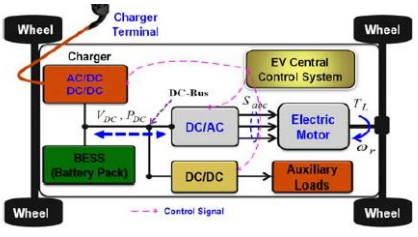

Figure 1: Electrical components of an EV

Sources: www.googleimages .com/ EV components

It consist of an electric motor drive, Battery energy storage system (BESS), Charging system, EV central control system. EV have fewer moving parts, thus it requires minimum maintenance. The biggest advantage of using an electric vehicle is its green credential. Hence it is also called zero-emission vehicles. There are some specific factors that make the EVs' performance lag behind the ICE vehicles this includes limited cruising range and energy-saving strategy, charging and discharging rate, overall system protection and ride comfort.

PERMANENT MAGNET SYNCHRONOUS MOTOR (PMSM)

The permanent magnet synchronous motor is considered as the potential candidates for EV applications. This is due to their compact structure with small size and weight, high torque to inertia ratio, high efficiency, wide speed range, low noise and robust operations. The PMSM cross section is shown in figure 2.

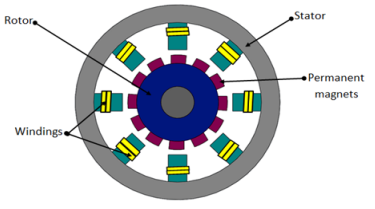

Figure 2: PMSM cross section

Sources: www.googleimages .com/ PMSM cross section

The PMSM uses permanent magnet embedded in steel rotor to create a constant magnetic field. The stator carries windings connected to an AC supply to produce a rotating magnetic field. At synchronous speed the rotor poles lock to the rotating magnetic field. PMSM is used in applications where fast and accurate torque control is required. A permanent magnet synchronous motor is also called as brushless permanent magnet sine wave motor. A sine wave motor should have

1. Sinusoidal or quasi-sinusoidal distribution of magnetic flux in the air gap.
2. Sinusoidal or quasi-sinusoidal current wave form.
3. Quasi-sinusoidal distribution of stator conductors.

Figure 2 shows the cross section of a PMSM. It consists of a stationary member of the machine called stator. Yoke completes the magnetic path. Lamination thickness depends upon the frequency of the armature source voltage and cost. Armature windings are generally double layer and lap wound. Individual coils are connected together to form phasor groups. Phasor groups are connected together to form star, delta, two phase or single windings. AC windings are normally short pitched to reduce harmonic voltage developed in the windings.

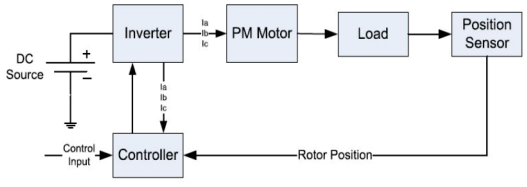

Figure 3: PMSM drive configuration

Sources: www.googleimages .com/ PMSM drive configuration

Figure 3 shows the PMSM drive configuration. It consists of a DC power supply connected to an inverter, the inverter converts the DC supply to AC supply and then it is fed to the PMSM.

MODEL OF PMSM

The assumptions used for modelling PMSM is given below

1. Effect of saturation is neglected.
2. Induced EMF is sinusoidal.
3. Eddy current and hysteresis loss is negligible.
4. There is no effect of field current dynamics.

The modelling is done in the *dq* reference frame. The stator equations of the induction machine in the rotor reference frames using flux linkages are taken to derive the model of PMSM. The rotor frame of reference is chosen because the position of the rotor magnets determines the instantaneous induced emfs and subsequently the stator currents and torque of the machine.

Voltage equations in rotor reference frame are given by

$$V_q = R_q i_q + \omega_r \lambda_d + P\lambda_q \quad \text{.....(1)}$$

$$V_d = R_d i_d - \omega_r \lambda_q + P\lambda_d \quad \text{.....(2)}$$

The flux linkages are given by

$$\lambda_q = L_q i_q \quad \text{.....(3)}$$

$$\lambda_d = L_d i_d + L_m \lambda_f \quad \text{.....(4)}$$

Substituting the flux linkages in equation (1) and (2)

$$V_q = R_q i_q + \omega_r (L_d i_d + \lambda_f) + P L_q i_q \quad \text{...(5)}$$

$$V_d = R_d i_d - \omega_r L_q i_q + P(L_d i_d + \lambda_f) \quad \text{...(6)}$$

Arranging above equations in matrix form

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_q + PL_q & \omega_r L_d \\ -\omega_r L_q & R_d + PL_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_f \\ P\lambda_f \end{bmatrix}$$

The developed motor torque is given by

$$T = \frac{3}{2}\frac{P}{2}(\lambda_d i_q - \lambda_q i_d) \quad \text{.....(7)}$$

The mechanical torque equation is

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \quad \text{.....(8)}$$

By using the above equations a PMSM model is developed in Matlab Simulink. The PMSM model is divided into a mechanical model and an electrical model.

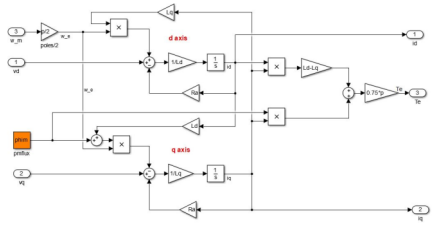

Figure 4: PMSM electrical model

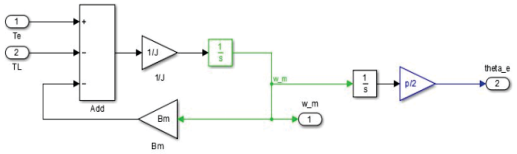

Figure 5: PMSM mechanical model

DIRECT TORQUE CONTROL (DTC)

The principle of direct torque control (DTC) is to directly select voltage vectors according to the difference between reference and actual value of torque and flux linkage. DTC is basically divided into two which includes the DTC with space vector modulation and the DTC with hysteresis modulation. Here DTC with space vector modulation is being used which is shown in fig 6.

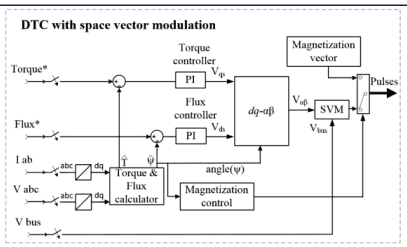

Figure 6: DTC with space vector modulation

Sources: in.mathworks.com

The classic DTC technique selects as the new voltage vector the one that maximizes the flux and torque error correction, and minimizes the number of commutations required to change from the old to the new inverter output. Each vector will produce a different change depending on the angular region where stator flux is located.

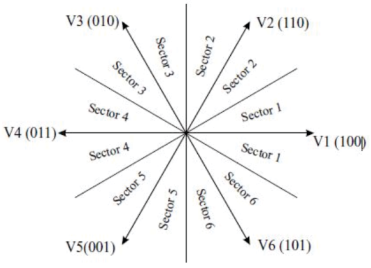

Figure 7: Voltage space vectors with corresponding sectors

Sources: www.googleimages .com/ sector selection

The flux and torque output is estimated by using the Torque and flux estimator/calculator. It is estimated by using the following equations

$$\varphi_d = \int (v_d - r_s i_d) dt \quad \text{.....(9)}$$

$$\varphi_q = \int (v_q - r_s i_q) dt \quad \text{.....(10)}$$

From equations 9 and 10 the value of stator flux can be determined.

$$\varphi_s = \sqrt{\varphi_d^2 + \varphi_q^2} \quad \text{.....(11)}$$

The torque output is estimated by using the equation

$$T_e = \frac{3}{2} P(\varphi_d i_q - \varphi_q i_d) \quad \text{.....(12)}$$

Here P is the pole pair

INTEGRAL CONTROL

The integral controller is a device that produce an output signal consisting of a single term which is proportional to the integral of the input signal. If *e(t)* ils the input signa and *u(t)* is the output signal, then it is given by

$$u(t) \alpha \int e(t) dt \quad \text{.....(13)}$$

Thus it becomes

$$u(t) = K_I \int e(t) dt \quad \text{.....(14)}$$

Here K_i is the Integral constant or gain.

On taking the laplace transform of equation 14

$$U(s) = \frac{K_i}{s} E(s) \quad \text{.....(15)}$$

Thus we obtain

$$\frac{U(s)}{E(s)} = \frac{K_i}{s} \quad \text{.....(16)}$$

The integral controller reduces the steady state error. The introduction of integral controller increases the order and type of the system by one.

SIMULATION RESULTS

At first the PMSM drive circuit is simulated by using Matlab Simulink. The output torque wave form is shown in figure 8.

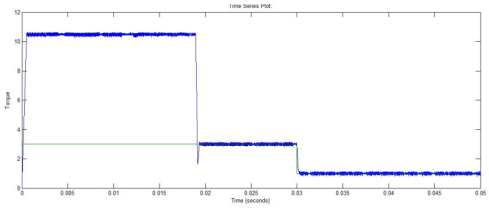

Figure 8: Output torque waveform

Here the green line represents the reference torque and the blue wave represents the actual torque output. The actual torque contains large quantity of ripples. It is always better to reduce the ripple content present in the torque waveform. In order to achieve this we implement the direct torque control.

The output current and speed wave form of the PMSM drive is shown in figure 9 and 10 respectively.

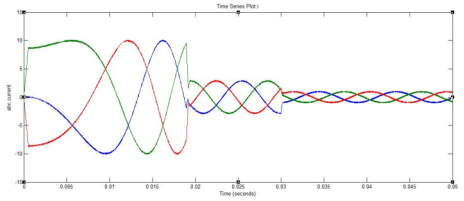

Figure 9: Output current waveform

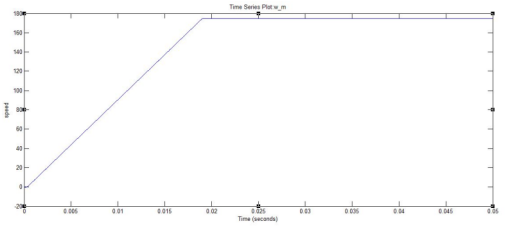

Figure 10: Output speed waveform

Now in order to reduce the ripple content in the torque output and to obtain good dynamic response, direct torque control is implemented in PMSM drives. This is simulated in Matlab Simulink and the following results are obtained.

The output torque waveform is obtained as shown in figure 11.

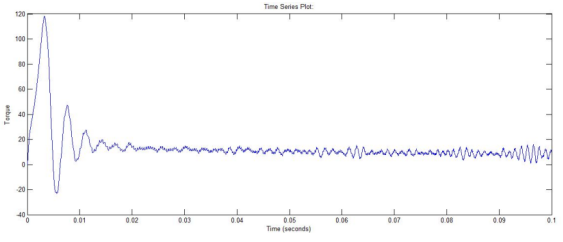

Figure 11: Output torque waveform after implementing DTC

Now the output current and speed waveforms are obtained as shown in figure 12 and 13.

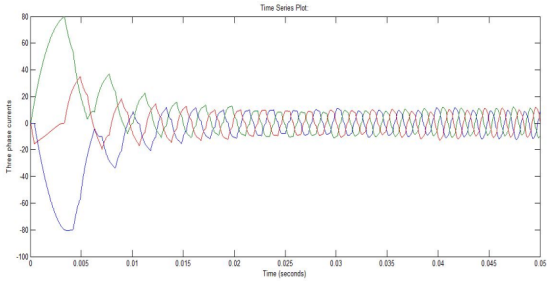

Figure 12: Output current waveform after implementing DTC

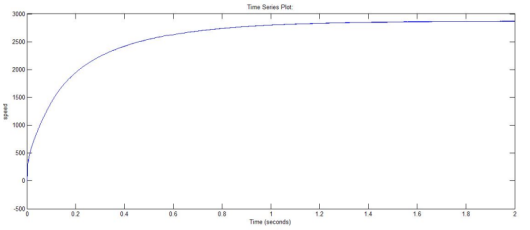

Figure 13: Output speed waveform after implementing DTC

The ripple content in the torque output can be further reduced by using an integral controller.

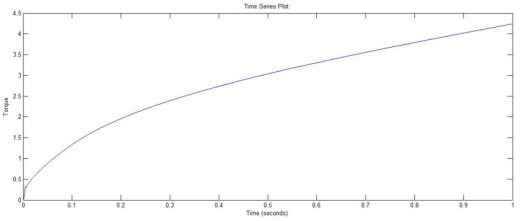

Figure 14: Output torque waveform after using an integral controller

Figure 14 shows that the ripple content in the torque output is reduced by using an integral controller. The output current and speed waveform will remain the same as shown below.

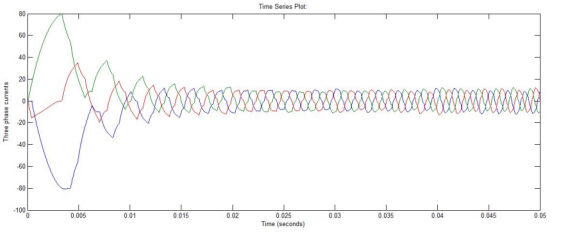

Figure 15: Output current waveform after using an integral controller

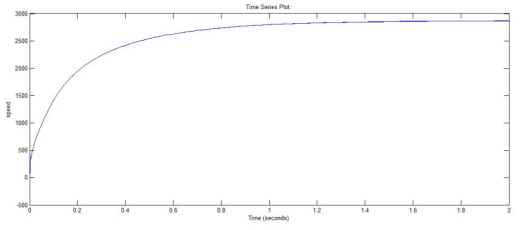

Figure 16: Output speed waveform after using an integral controller

CONCLUSION

This paper presents the direct torque control of PMSM in electric vehicle and reducing the torque ripple using an integral controller. The PMSM drive is mathematically modelled and simulated in Matlab Simulink. In order to improve the dynamic response, torque output and control of the PMSM the DTC is implemented. The torque output obtained after implementing DTC also shows the presence of ripple contents. Thus we introduce an integral controller which reduces the ripple content present in the torque output. The simulation results shows that the ripple content in the torque output is being reduced significantly.

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