Comparative Study of Control Strategies for Permanent Magnet Motors

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ABSTRACT

This paper presents a comparative study on widely used control schemes for permanent magnet (PM) motors. Both brushless DC (BLDC) motor and permanent magnet synchronous motor (PMSM) are considered. The comparison is based on various criteria such as steady state characteristics, dynamic performance and parameter sensitivity. Furthermore, the calculation cost for each scheme implementation is compared based on a sampling cycle and the common digital signal processor (DSP).

The six-step method of BLDC control, the field oriented control (FOC) and the direct torque control (DTC) methods of PMSM are analysed theoretically and compared. Based on these basic schemes, the differences between BLDC and PMSM are illustrated and the performances of both FOC and DTC for PMSM drive are compared. An analysis of the calculation cost of each type of drive system is carried out.

Then some reported modifications for these strategies are investigated such as space vector pulse-width modulation (SVPWM) for FOC, space vector modulation (SVM) DTC and discrete SVM DTC. The modified performances of different methods are compared not only with the sine PWM (SPWM)-FOC and basic DTC schemes but also with each other considering the operation cost in real system.

All above strategies are theoretically analysed and simulated based on MATLAB/SIMULINK. A comprehensive comparison of the calculation cost of the control schemes in real drive system is presented. Thus, this paper may provide useful information for researchers and product engineers about control strategies for PM motor drives.

1 INTRODUCTION

Permanent magnet (PM) motor, which has found wide applications, is a competitive alternative for induction motor because of its high power density (compactness), high efficiency, easy control, high torque-to-inertia ratio and high reliability.

The PM motors can be categorised according to the shape of the back electromotive force (EMF) waveform. The first category uses continuous rotor position feedback information to control current commutation in the stator windings. The ideal motor back EMF is sinusoidal, so that when sinusoidal currents are input, a constant torque is produced with very low ripple. It is usually called permanent magnet synchronous motor (PMSM) or brushless AC (BLAC) motor. The second category is based on position feedback that is not continuous, but rather obtained at fixed points, for example every 60 electrical degrees. This is called the brushless DC (BLDC) motor, in which typically the current is held constant for at least 120 electrical degrees and hence is approximately rectangular in shape and the ideal back EMF is trapezoidal.

This paper reviews the widely used control schemes for different types of PM motors. A comparison is made in terms of the basic control characteristics, dynamic performance and parameter sensitivity. Furthermore, the calculation cost for each scheme implementation is compared based on a sampling cycle. It is assumed that a digital signal processor (DSP) with modified Harvard architecture is used.

2 MATHEMATIC MODELS AND CONTROL METHODS

2.1 BLDC

The phase variables are used to model the BLDC motor as they can account for the real waveforms of the back EMF and phase current. The voltage equation of the BLDC motor can be written as

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R+pL_s & 0 & 0 \\ 0 & R+pL_s & 0 \\ 0 & 0 & R+pL_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

where V_a, V_b, V_c are the phase voltages, i_a, i_b, i_c are the phase currents, e_a, e_b, e_c are the phase back EMF, R is the phase resistance, L_s is the synchronous inductance per phase including both the leakage and armature reaction inductances, and p represents d/dt. The electromagnetic torque is given by

$$T_e = (e_a i_a + e_b i_b + e_c i_c)/\omega_m \tag{2}$$

where ω_m is the mechanical angular speed of the rotor.

The BLDC drive system is operated with the feedback information of rotor position, which is obtained at fixed points, typically every 60 electrical degrees for commutation of the phase currents. The BLDC motor requires that quasi-rectangular shaped currents are fed into the machine. Alternatively, the voltage may be applied to the motor every 120 degrees, with a current limit to hold the currents within the motor's capabilities. Because the phase currents are excited in synchronism with the constant part of the back EMF, a constant torque is generated.

2.2 PMSM

2.2.1 FOC control of PMSM

As to the widely known three-phase PMSM, the voltage equations for the stator windings in the stationary reference frame (a, b, c) can be written in the matrix form as

$$V_{abcs} = R_s I_{abcs} + \frac{d}{dt}\lambda_{abcs} \tag{3}$$

where V_{abcs} is the phase voltage, R_s the stator winding resistance per phase, I_{abcs} the phase current, and λ_{abcs} the flux linkage of phase winding.

The field oriented control (FOC) or vector control is the most popular control method of PMSM [1]. The FOC operates by controlling the components of the stator currents, represented by a vector in a rotating reference frame d-q aligned with the rotor flux. The voltage and torque equations can be expressed in the rotor reference frame in order to transform the time-varying variables into steady state constants. By using Clark and Park Transforms, the three-phase variables in the stationary frame could be transformed to the rotor reference frame. Then the electromagnetic torque expression is

$$T_e = \frac{3}{2}\frac{p}{2}\left(\lambda_m i_{qs}^T + \left(L_d - L_q\right) i_{qs}^T i_{ds}^T\right) \tag{4}$$

where P is the number of poles, i_{ds}^{T} and i_{qs}^{T} are the components of the current vector, and L_d and L_q are the inductances in the rotor d-q reference frame, respectively. L_d and L_q are equal for the surface mounted PMSM, so the torque is proportional to the q-axis current only. This results in the method of controlling the q-axis current for regulating the torque in the rotor reference frame.

Fig. 1 shows the diagram of FOC controller PMSM drive system. The d-axis current is set to zero while the q-axis current is controlled by a PI controller with the reference speed. Then the reference voltage vector is sent to a PWM generator to control the inverter. Recently, the space vector PWM (SVPWM) theory demonstrated some improvement for both the output crest voltage and the harmonic copper loss. The maximum output voltage based on the SVPWM is 1.115 times that with the conventional sinusoidal modulation. In the SVPWM theory the motor voltage vector is approximated by a combination of 8 switching patterns of the inverter.

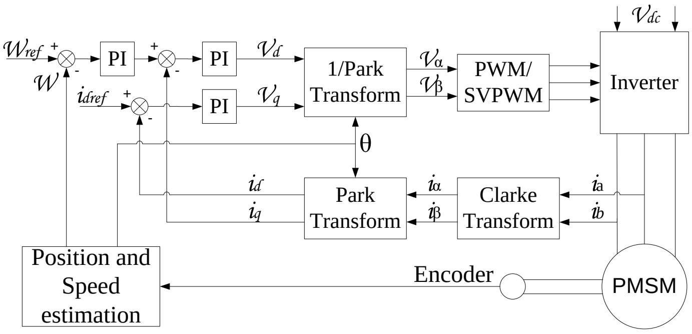


Fig. 1-FOC control system diagram

2.2.2 DTC control of PMSM

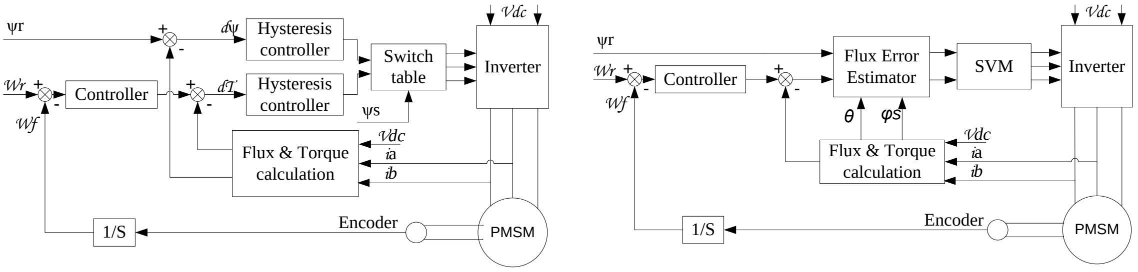
The DTC method was developed by Takahashi [2] and Depenbrock [3] firstly for induction motors aiming to improve the dynamic performance of the drive system. The basic idea of DTC for induction motor is to control the torque and flux linkage by selecting the voltage space vectors properly, which is based on the relationship between the slip frequency and torque. It has been proven that the DTC scheme could be modified for PMSM drive.

In the DTC strategy, the flux linkage and torque is calculated in the stator reference frame, α-β frame. The stator flux linkage of a PMSM can be expressed as

$$\varphi_s = \int (v_s - Ri_s)dt \tag{5}$$

and the torque can be written as

$$T_e = \frac{3}{2} p(\varphi_\alpha i_\beta - \varphi_\beta i_\alpha) \tag{6}$$



(a) (b)

Fig. 2-Diagrams of DTC drive system for PMSM
(a) Basic DTC scheme; (b) SVM DTC scheme

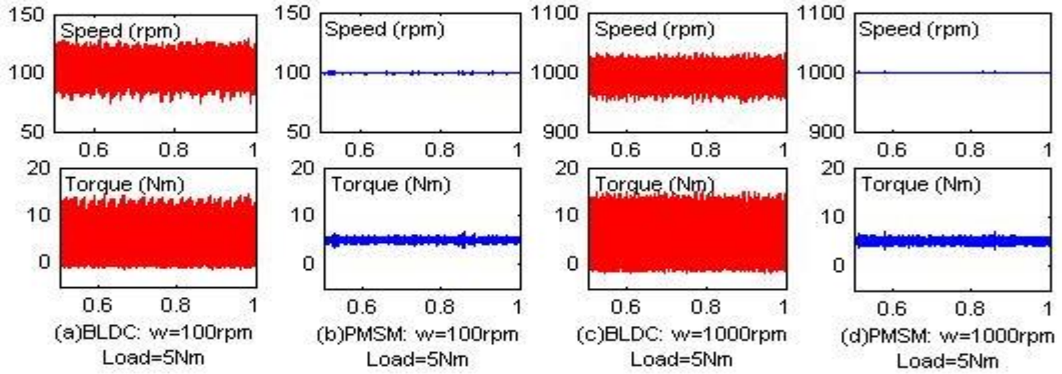
The space vector theory was introduced into DTC scheme as space vector modulation (SVM), firstly for induction motors by Habetler [4]. The basic idea of SVM is to adjust the flux speed by mean of inserting zero voltage vectors to control the electromagnetic torque generated by the induction motor. The selection rule is based on the error vector between the expected flux linkage vector and the estimated flux linkage vector. DTC systems for PMSM with both basic scheme and SVM method are shown in Fig. 2.

3 COMPARISON

The PM motor drive with different control schemes is simulated by using the MATLAB/SIMULINK software package, providing a complete analysis of the steady state and dynamic performances of the PM motor drive.

3.1 Steady state performance

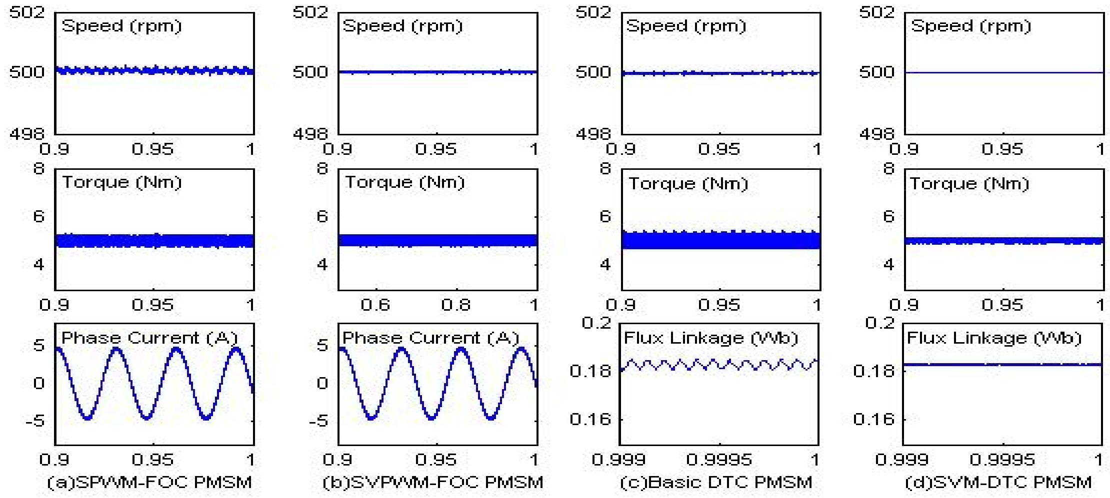
A six-step controlled BLDC system model is developed compared with a vector controlled PMSM system by using SPWM method. The steady state performance at two speeds is shown in Fig. 3.



(a)BLDC: w=100rpm Load=5Nm
(b)PMSM: w=100rpm Load=5Nm
(c)BLDC: w=1000rpm Load=5Nm
(d)PMSM: w=1000rpm Load=5Nm

Fig. 3-Steady state performance of BLDC and PMSM (SPWM), with a load of 5Nm
(a) BLDC w=100rpm; (b) PMSM w=100rpm; (c) BLDC w=1000rpm; (d) PMSM w=1000rpm.

As shown in Fig. 3, for a fixed sampling time, the performance of the PM motor at high speed is always better than that at low speed. There is less torque ripple and the speed is more stable. On the other hand, PMSM has better performance than BLDC at steady state. The maximum torque error of BLDC at steady state is about 8 times that of PMSM and the speed error is about 10 times.



(a)SPWM-FOC PMSM
(b)SVPWM-FOC PMSM
(c)Basic DTC PMSM
(d)SVM-DTC PMSM

Fig. 4--Steady state performance of PMSM with different control schemes
(a) SPWM-FOC; (b) SVPWM-FOC; (c) Basic DTC; (d) SVM-DTC

For the PMSM, four different drive schemes are developed and compared, i.e. SPWM of FOC, SVPWM of FOC, basic DTC and SVM DTC. Their output torques, rotor speeds and phase currents (or flux linkages) at w=500 rpm are shown in Fig. 4. The reference speed is 500 rpm and the load is 5 Nm. For vector control, the controlled objective is the current. Compared to the SPWM, the SVPWM scheme achieves better performance with less current harmonics and more stable output torque. For the basic DTC method, the controlled objective is the output torque and the torque error depends on the hysteresis controller band width. A smaller band width could achieve more stable torque output but increase the switching frequency. In Fig. 4(c), the band value of torque controller is ±0.2. By applying the SVM method into DTC, the inverter switching frequency can be fixed. Obviously, the torque and flux ripples are reduced compared to the basic DTC.

3.2 Transition performance

The comparison of the dynamic performances of BLDC and PMSM is shown in Fig. 5. A load of 5 Nm is added to the motor at t=0.5 s. The transition performances at both low and high speeds are compared. The response of BLDC is slower because it is six-step controlled. In other words, the control resolution is 60 electrical degrees.

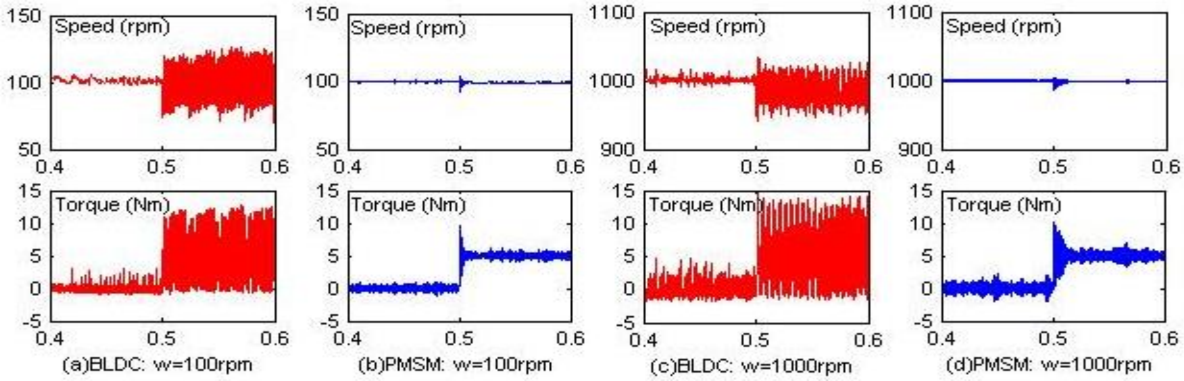


Fig. 5 Dynamic performance of BLDC and PMSM with a load step of 5 Nm at t=0.5 s.
(a) BLDC w=100 rpm; (b) PMSM w=100 rpm; (c) BLDC w=1000 rpm; (d) PMSM w=1000 rpm.

For the PMSM drive, the torque response of DTC is faster than that of FOC. Because the controlled objective of DTC is the torque, any change of the load could be tracked quickly, as demonstrated in Fig. 6. On the other hand, in the vector control scheme, the controller can only adjust the current to follow the load change after the feedback current is changed. There is a delay in the output torque response.

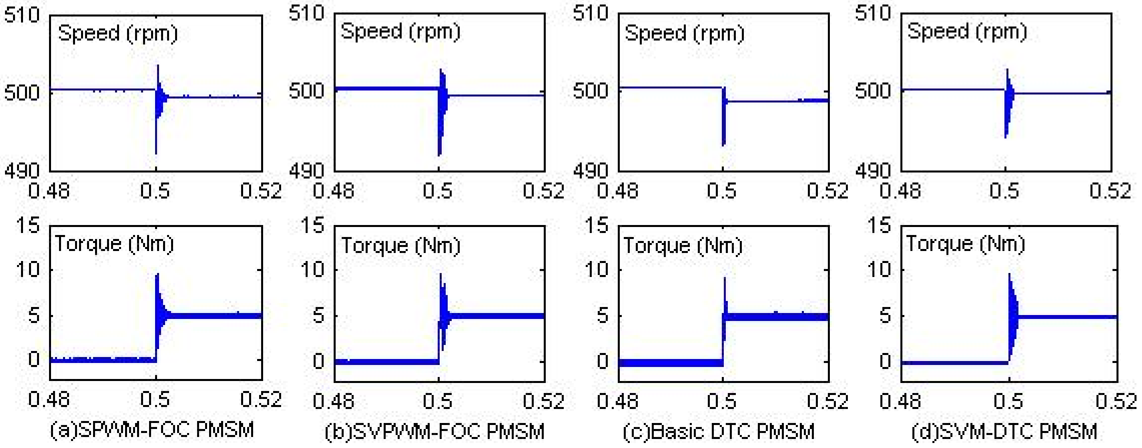


Fig. 6 Dynamic performance of PMSM, with a load step of 5 Nm added at t=0.5 s.
(a) SPWM-FOC; (b) SVPWM-FOC; (c) Basic DTC; (d) SVM-DTC

3.3 System control cost

For industrial application, the calculation cost of a control system is also important. Less computation cost in every sampling cycle means less control delay, higher control efficiency and lower product cost. For BLDC, the phases commutate every 120 electrical degrees and there is only one current PI controller, so its calculation delay is the least. The delay of DTC is generally less than that of FOC mainly due to the absence of reference frame transformation and fewer PI controllers in DTC. When the SVPWM is applied, the calculation cost might be increased both in FOC and DTC.

4 CONCLUSION

This paper presents a comprehensive comparison of different control strategies for PM motor drives. Based on the classification of PM motors as BLDC and PMSM, the widely used control schemes for these motors are modelled, simulated and compared in terms of the steady state performance, dynamic performance and computation cost. The comparison of the six-step control of BLDC and the basic vector control of PMSM reveals that the PMSM has better performance although the system cost is higher. However, BLDC is a good choice when simple implementation is required. It is also illustrated that DTC method has better dynamic performance and lower calculation cost than FOC while the later has much better steady state output. After applying the SVM method to FOC and DTC, it is clear that the SVM scheme can improve the system performance although the computation cost is several times higher. Considering the fixed switching frequency, SVM DTC scheme is usually used for high performance and fast torque response applications.

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