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# Modified Direct Torque Control of Permanent Magnet Synchronous Motor by using voltage vectors of variable amplitude and angle

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***Abstract—In conventional direct torque controlled (DTC) permanent magnet synchronous motor drive (PMSM), there is usually unwanted torque and flux ripple. A modified direct torque control (DTC) for permanent-magnet synchronous machines, which enables important torque- ripple reduction by using voltage vectors with variable amplitude and angle, is proposed in this paper. In the proposed DTC, the magnitude of torque and flux errors are differentiated and employed to regulate the amplitude and angle of the output voltage vectors, which are finally synthesized by space vector modulation (SVM). The proposed DTC method is comparatively investigated with conventional DTC based on theory analysis and computer simulation. Simulations results validate the effectiveness of the proposed schemes in this paper.***

**Index Terms—*Direct Torque Control(DTC), Maximum torque per ampere(MTPA), Permanent Magnet Synchronous Motor(PMSM),Space Vector Modulation(SVM).***

## I. INTRODUCTION

Permanent magnet synchronous motor (PMSM) drives are replacing classic dc and induction machine (IM) drives in many industrial applications like industrial robots and machine tools. Advantages of PMSMs include high power factor, high efficiency, high power density, reliability and low inertia. Because of these advantages, permanent magnet synchronous motors are indeed excellent for use in high-performance servo drives where a fast as well as accurate torque response is required. In permanent magnet synchronous motor drives, the electromagnetic torque is usually controlled indirectly via the stator current components in a reference frame fixed to the rotor flux field. Direct Torque Control was introduced by I. Takahashi and T. Noguchi [3] as a new control strategy for induction motor drives fed by Voltage Source Inverters. Because of the merits of the earlier, recently DTC has been extended from conventional induction motor (IM) drive to permanent magnet synchronous motor (PMSM) drive [4]. DTC can provide extremely high dynamic response with very simple structure, i.e, there is no need of rotary coordinate transformation, inner current regulator, or pulsewidth modulation (PWM) block, fast torque response and good robustness. However, conventional DTC employs two hysteresis comparators and a heuristic switching table to obtain quick dynamic response, which results in undesired torque and flux ripple, variable switching frequency, vibration and acoustic noises.

An effective modality for reducing the torque ripple without using a high sampling frequency is to calculate a proper reference voltage vector that can produce the desired torque and flux values, and then given to the inverter using SVM. This approach is given in the literature as DTC-SVM [7]. In the SVM-based DTC schemes, rotary coordinate transformation is often needed, which is more computationally intensive than the conventional DTC.

With multi-level inverter, there will be more voltage space vectors available to control the flux and torque. Therefore, a smoother torque can be obtained, as reported in [14]. However, more power switches are needed to achieve a lower ripple and almost fixed switching frequency, increasing the system cost and complexity. Another method is discrete SVM which has an accurate switching table obtained by dividing one sampling period into more intervals. It reduces torque ripple but complexity in switching table increases when number of intervals increases. Recently, predictive control was introduced to achieve high performance control [8]. This kind of method is similar to DTC only in that they both directly manipulate the final voltage vector. In [8], by evaluating the defined cost function of each possible switching states, the state best satisfying the performance requirement is selected. Indeed of this, it depends mainly on accuracy of system parameters.

Another category of modifying DTC is changing the vector length by adjusting the duty ratio of active vector. Duty ratio can be obtained by various methods such as fuzzy logic adaptation, equalizing the mean torque with reference value in one cycle, torque ripple minimization etc. All these methods require lots of motor parameters, so it is complicated.

In a conventional DTC[11] drive the basic voltage model based flux estimation is carried out by integrating the back emf of the machine. When the stator flux is indirectly estimated from the integration of the back emf, any DC offset is also integrated and would eventually lead to a large drift in the stator flux linkage. A commonly employed solution is to replace a pure integrator with a low pass filter, however it is achieved at the expense of deteriorated low speed operation of the drive, when the stator frequency of the drive is lower than the cut off frequency of the low pass filter, so compensation is required.

In this paper a simple method is proposed for the calculation of the reference voltage vector, which maintains the conventional DTC principle regarding the decoupled torque and flux control. Conventional switching table and hysteresis comparators are eliminated and also difficulty of variable switching frequency is eliminated by using space

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vector modulation. The amplitude and angle of voltage vector is obtained from torque and flux errors only and is synthesized by space vector modulation. It is the aim of this paper to reduce the torque while preserving the structure simplicity as much as possible. The proposed scheme is simulated for inverter-fed PMSM drive.

## II. MODELING OF PMSM

Rotor magnetic flux vector $\psi_M$ and stator magnetic flux vector $\psi_s$, can be represented on stator flux (xy) reference system and rotor flux (dq), as shown in Figure 1.The angle δ between the stator and rotor magnetic fluxes, is the load angle. and is constant for a constant load torque[2].In this case both the stator and the rotor fluxes rotate at constant speed. But load angle varies under different loads. Either the stator current rotation speed or the variation of load angle δ is controlled in order to control the increase of the torque.

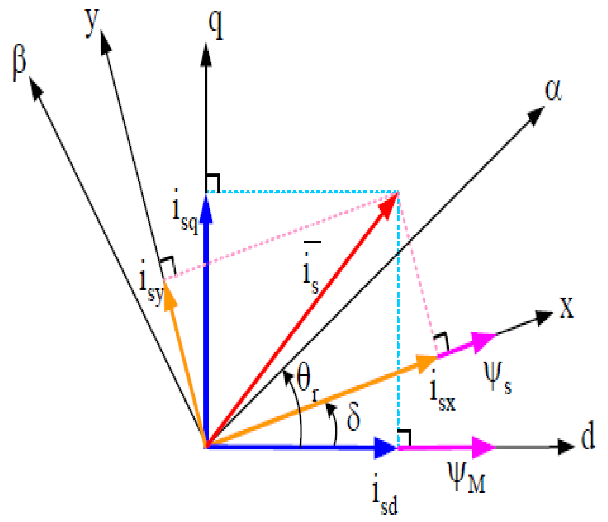

Fig. 1. Stator and rotor magnetic fluxes in different reference systems

The equations in the rotor reference frame are as follows:

$$u_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_r \psi_{qs} \qquad (1)$$

$$u_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_r \psi_{ds} \qquad (2)$$

and stator flux equations are

$$\psi_{ds} = L_{ds} i_{ds} + \psi_f \qquad (3)$$

$$\psi_{qs} = L_{qs} i_{qs} \qquad (4)$$

The electromagnetic torque is given by

$$\begin{aligned} T_e &= \frac{3}{2} p\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \\ &= \frac{3}{2} p\left[\psi_f i_{qs} + \left(L_{ds} - L_{qs}\right) i_{ds} i_{qs}\right] \\ &= \frac{3p|\psi_s|}{4L_{ds}L_{qs}}\left[2\,\psi_f L_{qs}\sin\delta + |\psi_s|\left(L_{ds} - L_{qs}\right)\sin 2\delta\right. \end{aligned} \qquad (5)$$

and it is composed of two parts: the permanent-magnet torque and the reluctance torque caused by the rotor saliency.

The d-axis and q-axis inductances i.e $L_d$ and $L_q$ are equal to synchronous inductance ($L_s$) for surface monted PMSM without saliency. Therefore the reluctance torque becomes zero and torque is simplified as

$$T_e = \frac{3}{2} p \psi_f i_{qs} = \frac{3}{2} p\,(\psi_f |\psi_s| \,/\, L_s)\ \sin\delta \qquad (6)$$

## III. CONVENTIONAL DTC SCHEME

It controls the stator flux linkage and the torque directly without using current control loop. This is possible by controlling the power switches directly using the outputs of hysteresis comparators for the torque and the module of the stator flux linkage and selecting an appropriate voltage vector from a preset switching table. The direct torque control (DTC)[5],[10] is based on the direct calculus of the instantaneous torque from the measurement of the voltages and currents at the machine terminals. Fig 2 shows a classic scheme of DTC control.

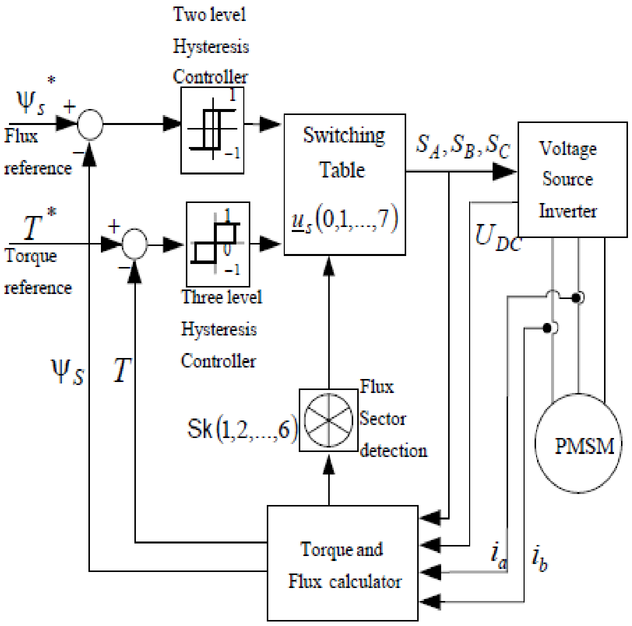

Fig. 2. Block diagram of conventional DTC

It consists of stator flux and torque estimators, torque and flux hysteresis comparators, a heuristic switching table and a voltage source inverter (VSI). The basic idea of DTC is to choose the best voltage vector in order to control both stator flux and electromagnetic torque of machine simultaneously.

The stator voltage space vector components in the stationary reference frame are calculated as shown below

$$u_{s\alpha} = \frac{2}{3} U_{DC}\ \left(S_A - \ (S_B - S_C)/2\ \right) \qquad (7)$$

$$u_{s\beta} = \frac{2}{3} U_{DC}\ (\ S_B - S_C)/\sqrt{3} \qquad (8)$$

where $S_A$ , $S_B$, $S_C$ denotes the switching states of inverter, in which $S_i$ =1(A,B,C) if the upper leg switch is on and $S_i = 0$, if the upper leg switch is off.

The stationary frame (α-β) components of the stator current vector are calculated using below equations supposing the motor has the star connection.

$$i_{s\alpha} = i_{sA} \qquad (9)$$

$$i_{s\beta} = (i_{sA} + 2 i_{sB})/\sqrt{3} \qquad (10)$$

The stator flux are

$$\psi_{s\alpha} = \int (u_{s\alpha} - R_s i_{s\alpha})dt \qquad (11)$$

$$\psi_{s\beta} = \int (u_{s\beta} - R_s i_{s\beta})dt \qquad (12)$$

The α-β components of the stator flux are used to determine the sector in which the flux vector are located. The magnitude of the stator flux and electromagnetic torque are calculated as follows

$$|\psi_s| = \sqrt{\psi_{s\alpha}^2 + \psi_{s\beta}^2)} \qquad (13)$$

$$T_e = \frac{3}{2} p\left(\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}\right) \qquad (14)$$

where: P - number of pole pairs

Rs - Stator resistance

The calculated magnitude of stator flux and electric torque are compared with their reference values in their corresponding hysteresis comparators as are shown in fig.3.1. Finally, the outputs of the comparators and the number of sector at which the stator flux space vector is located are fed to a switching table to select an appropriate inverter voltage vector from the switching table. The vector selection in conventional DTC is shown in fig.3.

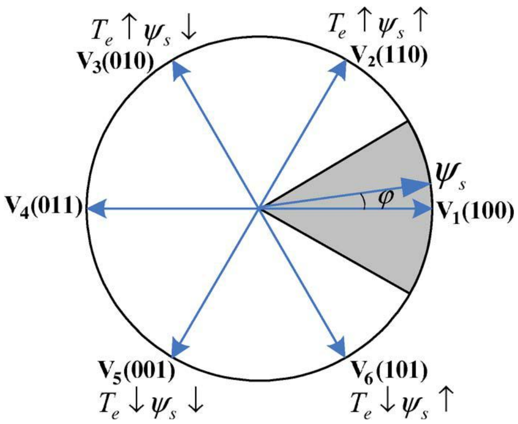

Fig. 3. Vector selection in conventional DTC

### A. *Shortcomings of conventional DTC*

Though the conventional DTC is simple, it has certain drawbacks. Firstly, it includes large torque ripples, variable switching frequency and acoustic noises. Secondly, the hysteresis comparators do not differentiate their amplitudes, it only consider the signs of torque and flux error. Thirdly, the switching table consists of limited number of voltage vectors with fixed length and angle.The modified DTC scheme proposed in this paper attempts to overcome all these drawbacks.

## IV. MODIFIED DTC SCHEME

The DTC scheme specified above is modified by eliminating switching table and hysterisis controllers and also fixed frequency is obtained by SVM. In this method, the amplitude of torque and flux errors are differentiated and is used to regulate the amplitude and angle of voltage vector which is finally synthesized by space vector modulation. The block diagram of proposed DTC is shown in fig. 4.

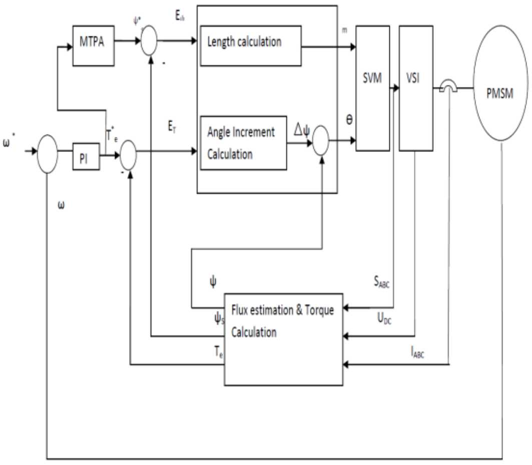

Fig.4. Block diagram of modified DTC

In this, the stator flux reference is determined from torque reference based on the principle of maximum torque per ampere (MTPA)[9],[12] in order to improve system efficiency. The relationship between torque and stator flux reference for surface PMSM is given by

$$|\psi_s^*| = \sqrt{\psi_f^2 + \left(\frac{L_{qs}T_e^*}{3/_{2}p\psi_f}\right)^2} \qquad (15)$$

### A. *Determination of Voltage-Vector Angle*

As per fig.3 the stator flux vector is located with in area ± 30, a fixed vector depending on the signs of torque and flux errors will be selected. But it fails to regulate torque accurately. Text heads organize the topics on a relational, hierarchical basis. For obtaining better performance, the angle of voltage vector is determined by using torque and flux errors and stator-flux position as shown in fig.5. If the torque and flux increases and stator flux angle ψ is known as shown in fig.5, the vector can be selected from shaded area I within the angle of ($\psi + 10^0, \psi + 80^0$).To avoid a sharp change in torque and flux, the range within ($\psi$, $\psi + 10^0$) and ($\psi + 80^0$, $\psi + 90^0$) is not taken.

The voltage vector angle increment from the view of torque regulation is expressed as

$$\Delta\psi_T = \left|\frac{E_T}{C_T}\right| . \frac{\pi}{2} = \left|\frac{(T_e^* - T_e)}{C_T}\right| . \pi/_2 \qquad (16)$$

where Te$^*$ - reference value for torque
$C_T$ - positive constant

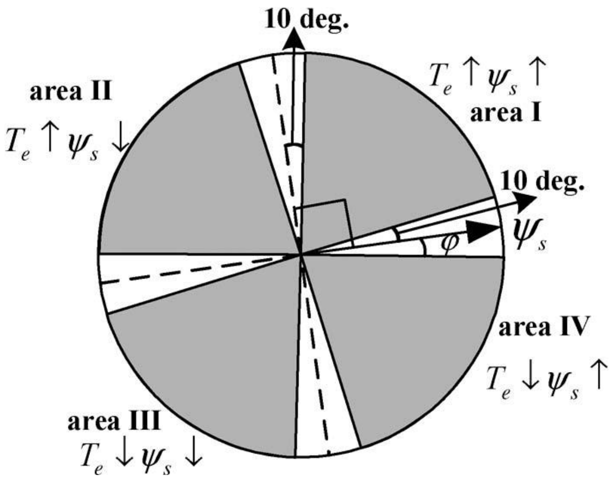

Fig.5. Vector selection in proposed DTC

From the view of stator flux regulation, the angle increment is negatively proportional to flux change and is expressed as

$$\Delta\psi_\psi = \left(1 - \left|\frac{E_\psi}{C_\psi}\right|\right) . \frac{\pi}{2}$$
$$= \left(1 - \left|\frac{(\psi_s^* - \psi_s)}{C_\psi}\right|\right) . \pi/_2 \qquad (17)$$

where $\psi_s^*$ is the reference value for flux and $C\psi$ is a positive constant.

The final voltage angle increment with respect to stator flux is given by

$\Delta\psi = k\Delta\psi_T + (1-k)\Delta\psi_\psi$ for area I
$\Delta\psi = k(\pi - \Delta\psi_T) + (1-k)(\pi - \Delta\psi_\psi)$ for area II
$\Delta\psi = -k\Delta\psi_T - (1-k)\Delta\psi_\psi$ for area III
$\Delta\psi = k(-\pi + \Delta\psi_T) + (1-k)(-\pi + \Delta\psi_\psi)$ for area IV

Where k is torque weighting factor and is normally taken as greater than 0.5.

### B. Determination of Voltage-Vector Amplitude

The voltage vector is determined not only by the angle but also by its amplitude.In this proposed method, the lenth of voltage vector is expressed as

$$m = \left|\frac{E_T}{C_T}\right| + \left|\frac{E_\psi}{C_\psi}\right| = \left|\frac{(T_e^* - T_e)}{C_T}\right| + \left|\frac{(\psi_S^* - \psi_S)}{C_\psi}\right| \quad (19)$$

where m is normalized with respect to maximum peak of phase voltage.

Tuning of $C_T$ and $C_\psi$ gives better steady state performance. Larger value of these will produce less ripples in torque.

### C. Voltage Vector

Number The voltage vector obtained after getting angle increment and amplitude is expressed in polar coordinates as

$$V = m \,.\, e^{j(\psi + \Delta\psi)} \quad (20)$$

which is synthesized by space vector modulation.

The main difference from SVM-DTC is it requires only torque and flux errors, no additional parameters or rotary transformation is not required. By applying equation(20) , the torque ripples can be reduced effectively which is explained in simulation results.

## V. SIMULATION RESULTS AND ANALYSIS

In order to show the performance improvement both conventional and proposed DTC shown in fig(2) and fig (4)were simulated using MATLAB/ Simulink environment. The motor parameters are listed in table I. The simulation results are depicted in Figs (6), (7), (8), and (9).

Table I . Motor and system parameters

| | |
|---|---|
| Number of pole pairs | 3 |
| Permanent magnet flux | 0.1057Wb |
| Stator resistance | 1.8Ω |
| d-axis and q-axis inductance | 45mH |
| Rated speed | 2000rpm |
| Rated Torque | 4.5Nm |
| Rated line-line voltage | 128V |
| Sampling period | 100µs |
| DC bus voltage | 72V |
| Torque constant gain | 2Nm |
| Flux constant gain | 0.1Wb |
| Torque weighting factor | 0.8 |

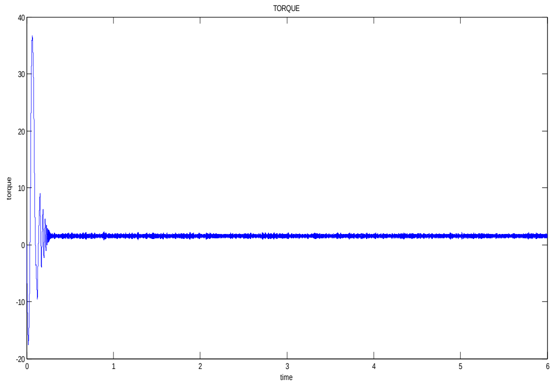

Fig (6) Torque response of conventional DTC

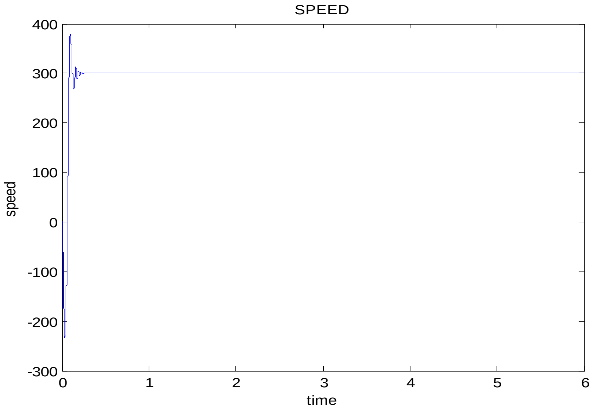

Fig (7) Speed response of conventional DTC

Fig (6) and (7) shows the performance of conventional DTC for a load torque of 1.5 Nm and a speed of 300 rpm.

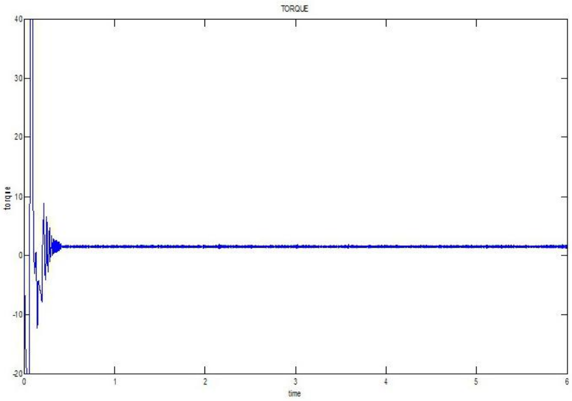

Fig (8) Torque response of proposed DTC

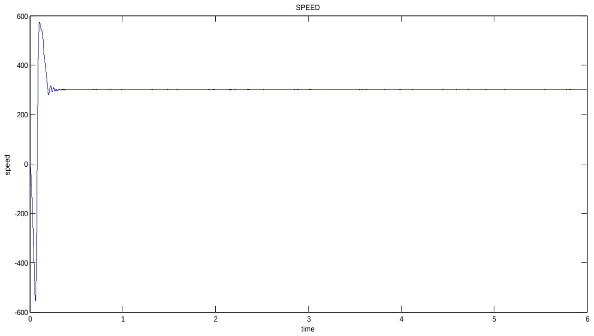

Fig (9) Speed response of proposed DTC

Fig (9) and (10) shows the steady state performance of proposed DTC for a load torque of 1.5Nm. From these figures it is shown that ripples in torque and speed are smaller than that of conventional DTC which confirms that the SVM method is a more effective way for accurate control of electromagnetic torque.

## VI. CONCLUSION

In this paper, a modified DTC has been proposed to overcome the drawbacks of large torque ripple and variable switching frequency. To control torque more accurately, both the amplitude and angle of voltage vector are regulated. This method requires no additional motor parameters. The performance of the modified DTC is comparatively investigated with conventional one. Simulation results prove that modified DTC has excellent steady state performance.

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