Improved Dynamic Performance of Permanent Magnet Synchronous Motor using Maximum Torque Per Ampere with reduced number of switches

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Abstract. To attain the excellent dynamic performance of any drive the torque ripples must be as minimum as possible. Otherwise which leads to oscillations in a speed profile and hence results in poor performance of a drive. The proposal of this work is to reduce as minimum as possible in torque ripples of a Permanent Magnet Synchronous Motor (PMSM) by means of a Five Level Space Vector Modulation (SVM). The SVM is used to generate gate pulses for an Inverter. Maximum Torque per Ampere (MTPA) is considered which ensures minimum ohmic losses. To reduce the reduces number of switching states and hence switching losses and to generate gate pulses to a five level inverter, three level inverter using SVM is taken as a reference. To verify the designed system, a simulator is implemented in MATLAB software environment and a comparison of results with and without MTPA control is being shown. Results clearly show that torque ripple, THD of motor phase voltage and current are greatly reduced under MTPA control.

1. Introduction
In applications such as transportation, efficiency and dynamic performance are very much essential for a PMSM drive. Owing to its advantages over other control techniques, DTC attracted many researchers both in industry as well as academia. But it is critical to find the online reference flux linkage in case of DTC control [1]. Whereas a reference torque is obtained from a reference current for all working operations such as constant torque, constant power from optimization techniques which ensures less computations [2]. This paper focuses on maximizing the efficiency of PMSM drive by advancing the current angle optimally with the help of current reference interpolation[3] [4].

Where information about the position of rotor is not required, scalar control along with MTPA is enough to obtain enhanced efficiency of a PMSM drive [5]. MTPA, is one of the optimized efficient control which enhances the efficiency of a PMSM drive with least copper losses [6]. Adaptive MTPA along with Radial Basis Neural Networks is proposed to obtain the better efficiency in [7]. Studies on Efficiency Characteristics is presented to obtain best possible working conditions for PMSM with interior rotor configuration [8]. Accurate current angle can be obtained directly from...
MTPA equation which ensures the fast detection of a current angle [9]. Stator flux reference is very much essential for a DTC, this can be obtained with the help of MTPA [10][11].

During dynamic operation, PMSM experiences pulsations in torque due to variations in its parameters [12]. Hence a control mechanism is required to track these variations to ensure the better performance of a drive under load perturbations especially when it is used in robotics, rolling mills and electric vehicles [13]. As DTC is independent of parameter variations, to certain extent these pulsations in torque and speed can be minimized [14] [15]. Variations in machine parameters, load perturbations causes a drift in stator current vector there by power factor [16].

2. Modelling of a complete system
In “simulation tool” helps to observe the dynamics of any drive in off line using novel methods and techniques which ensures not only the idea about the system but also reduces the cost and time. It makes ones job easy for hardware realization in real time environment once the model is finalized from simulation environment. In the proposed model results are obtained for both MTPA and without MTPA control technique using SVM. The modulation technique adopted here makes use of less switching states so as to lessen the ripple content in torque. The entire work is carried out using “MATLAB/SIMULINK” software tool. The obtained results clearly show that torque ripple, THD of motor phase current and voltage are greatly reduced under MTPA control.

3. Stator Flux Reference Generation
With MTPA, it is essential to implement an optimal switching strategy which guarantees least amount of stator copper losses so that maximum efficiency can be achieved. Else the desired electromagnetic torque should be obtained with minimum stator current. Thus, \( i_d \) is forced to zero by the appropriate switching vectors. The reference flux is obtained as follows:

\[
\lambda = \sqrt{(L_d i_d + \lambda_f)^2 + (L_q i_q)^2}
\]

With \( i_d = 0 \),
\[
\lambda = \sqrt{\lambda_f^2 + (L_q i_q)^2}
\]
also \( T_e \) reduces to equation (2)

\[
T_e = \frac{3}{2} p [\lambda_f i_q]
\]

From Eqn. (3), \( i_q \) is given by

\[
i_q = \frac{2T_e}{(3p \lambda_f)}
\]

Substituting \( i_q \) in Eqn. (2) yields

\[
\lambda = \sqrt{\lambda_f^2 + L_q^2 \left[ \frac{2T_e}{(3p \lambda_f)} \right]^2}
\]
$\lambda_{\text{ref}} = \sqrt{\frac{\lambda_f^2 + L_d^2 \left[ \frac{2T_{e \text{ ref}}}{3p \lambda_f} \right]^2}{}}$  \hspace{1cm} (6)

Reference torque $T_{e \text{ ref}}$ is calculated by converting the speed error into instantaneous torque using PI controller. From which the online reference flux $\lambda_{\text{ref}}$ is obtained Eqn. (6). The proposed diagram for implementation is depicted in Figure 1[16].

![Diagram](image)

**Figure 1.** Proposed Diagram

### 3.1 Multilevel Inverter

The inverters considered in this work are used to generate three level voltage and five level voltage waveforms using SVM technique to obtain gate pulses for the same. The switching combinations recommended for triggering the switches in the inverters are shown in (Table 1). Which illustrates the less number of switching combinations are used as compared to the conventional or actual switching combinations. this ensures the less switching losses than conventional switching combination. From Table 1, it is clear that only 54 switching states are required than 125 which increases the complexity of the system.

| DCMLI | SPWM | SVM | Switching States |
|-------|------|-----|------------------|
|       | Actual | Recommended |
| 3-Level | 12    | 12    | 27               | 27               |
| 5-Level | 24    | 24    | 125              | 54               |

### 4. Transient Response with MTPA

In MTPA, the desired electromagnetic torque is obtained with minimum stator current which is illustrated in Figures 2 and 3. The stator current without MTPA is 2A, whereas with MTPA it is less than 2A. Also the dynamic response is good with MTPA as the online stator flux is estimated every time. The transient responses obtained with MTPA at t=0.3 sec and $T_L=1.95$ Nm for 2-level Inverter are represented in Table 2.
Table 2: Transient response with MTPA with Two Level Inverter

| Description             | Without MTPA                                                                 | With MTPA                                                                 |
|-------------------------|------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Initial stator current  | High under no load conditions                                                | It is high initially and low, almost close to zero until load is applied at t=0.3 sec |
| Direct axis current     | High (approx 1A) with more oscillations                                    | Low, almost close to zero.                                               |
| Quadrature axis current | Approximately 1.5A with more oscillations                                   | Less than 2 A                                                            |
| Elect. Torque           | 1.95 Nm with oscillations                                                  | 1.95 Nm with steady response                                             |
| Speed                   | 1500 rpm with oscillations                                                 | 1500 rpm with steady response                                            |

Figure 2. Transient responses of $i_s$, $i_d$, $i_q$, $T_e$ and $\omega$ for 1500 rpm without MTPA for 2-level

Figure 3. Transient responses of $i_s$, $i_d$, $i_q$, $T_e$ and $\omega$ for 1500 rpm with MTPA for 2-level
In MTPA, the desired electromagnetic torque should be obtained with minimum stator current which is illustrated from Figures 4 to 11. The stator current without MTPA is 1.9A in three level SVM whereas with MTPA it is less than 1.8A with five level SVM. Also the dynamic response is good with MTPA as the on line stator flux is estimated every time. The THD of phase voltage is reduced to 2.47% and phase current is reduced to 3.56% respectively. The torque ripples are reduced from 27.27% to 6.5%. The observations made with and without MTPA when $T_L=1.0 \text{ Nm}$ at $t=0.3 \text{ sec}$ and $T_L=0.5 \text{ Nm}$ at $t=1\text{sec}$ respectively. The analysis with $T_L=1.0 \text{ Nm}$ at $t=0.3 \text{ sec}$ is given in Table 3. Observations with $T_L=1 \text{ Nm}$ at $t=0.3 \text{ sec}$.

**Table 3: Observations with $T_L=1 \text{ Nm}$ at $t=0.3 \text{ sec}$**

| Description         | 3 Level SVM | 5 Level SVM |
|---------------------|-------------|-------------|
|                     | Without MTPA | With MTPA   | Without MTPA | With MTPA   |
| $I_a(A)$            | 1.9         | 1.9         | 1.8          | 1.8         |
| $I_d(A)$            | 1.15        | 1           | 1.2          | 1           |
| $I_q(A)$            | 1.4         | 1.3         | 1.4          | 1.3         |
| $V_{ph}(\text{rms})$ in Volts | 168.7 | 168.6 | 168.8 | 168.8 |
| $I_{ph}(\text{rms})$ in (A) | 1.792 | 1.683 | 1.683 | 1.683 |
| THD for $V_{ph}$ (%) | 3.84 | 3.84 | 2.50 | 2.47 |
| THD for $I_{ph}$ (%) | 3.82 | 3.65 | 3.65 | 3.56 |
| Torque Ripple (%)   | 27.27       | 20          | 7.6          | 6.5         |

**Figure 4.** Transient responses of $I_s, I_a, I_d, I_q, T_e$ and $\omega$ for 3000 rpm without MTPA for 3-level with SPWM
Figure 5. Transient responses of $i_s$, $i_d$, $i_q$, $T_e$ and $\omega$ for 3000 rpm without MTPA for 3-level with SVM

Figure 6. Transient responses of $i_s$, $i_d$, $i_q$, $T_e$ and $\omega$ for 3000 rpm with MTPA for 3-level with SPWM

Figure 7. Transient responses of $i_s$, $i_d$, $i_q$, $T_e$ and $\omega$ for 3000 rpm with MTPA for 3-level with SVM
Figure 8. Transient responses of $i_s$, $i_d$, $i_q$, $T_e$ and $\omega$ for 3000 rpm without MTPA for 5-level with SPWM

Figure 9. Transient responses of $i_s$, $i_d$, $i_q$, $T_e$ and $\omega$ for 3000 rpm without MTPA for 5-level with SVM

Figure 10. Transient responses of $i_s$, $i_d$, $i_q$, $T_e$ and $\omega$ for 3000 rpm with MTPA for 5-level with SPWM
Figure 11. Transient responses of $i_s$, $i_d$, $i_q$, $T_e$ and $\omega$ for 3000 rpm with MTPA for 5-level with SVM

5. Conclusions
The proposed work is carried out with 3 level and 5 level inverters using SPWM & SVM based on MTPA technique. It is observed that the THD for phase voltage and currents are reduced to 2.47 and 3.56% respectively and torque ripples are reduced to 6.5%. Further these values can be improved by using Model reference Adaptive Controller. Without increasing the number switches, by introducing a phase delay number of levels in the output voltage can be achieved. By doing this, cost of the circuit can be reduced. Further in place of PI controller, fuzzy, hybrid fuzzy can be used.

6. References
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