Effect of Inverter Voltage Levels on Torque Ripples of PMSM Drive

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Abstract. This paper investigates the performance of Permanent Magnet Synchronous Motors (PMSM) in terms of torque ripples, a critical aspect affecting their operational efficiency and stability. Torque ripples in AC motors are primarily attributed to the switching action of the inverter Insulated Gate Bipolar Transistors (IGBTs), resulting in current fluctuations that directly influence motor torque. Mitigating these ripples is crucial for enhancing motor performance and reducing mechanical stress. This study focuses on utilizing multilevel inverters to minimize torque ripples by smoothing the motor current through harmonic elimination. Three different types of inverters, namely 2-level, 3-level, and 5-level inverters, are simulated to assess their impact on torque ripple reduction. The torque ripples were obtained from two methods where direct simulation is a method chosen and in second method, the average torque is subtracted from instantaneous torque samples. Stator currents are analyzed in the alpha-beta frame to evaluate the effectiveness of each inverter configuration in producing smoother current profiles and subsequently reducing torque ripples. Additionally, simulations are conducted under varying load torque conditions to assess the robustness and applicability of the proposed methodology across a wide range of operating conditions.

Keywords— Total Harmonic Distortions (THD), Modulation Index, Switching frequency, Sine Pulse Width Modulation.

1 Introduction

Permanent magnet synchronous motor (PMSM) drives [1] have found widespread use in industrial and transportation applications due to their advantages of compact size, high power density, and higher efficiency. The techniques used for speed control affect the PMSM drive's overall performance [2]. Knowing what causes torque ripples becomes important in applications where accurate torque control is critical. The term "torque ripple" describes the variation in torque output that occurs during motor operation and can cause unwanted vibrations, noise, and reduced performance. An important factor affecting torque ripples in PMSM drives is the inverter's voltage levels. The task of converting the source's DC power into AC power to run the motor falls to the inverter [3]-[4]. The motor currents' amplitude and frequency are directly impacted by the voltage levels produced by the inverter, which in turn affects the torque production and its smoothness. There are several different ways in which torque ripples and inverter voltage levels are related. Because of better motor control and less current ripple, higher voltage levels usually produce torque output that is smoother. Nevertheless, high voltage levels can cause problems in the motor windings, including increased losses, saturation, and overheating, all of which can result in higher torque ripples [5]. On the other hand, reduced voltage levels can result in insufficient torque generation, particularly when operating at high speeds or with heavy loads, which could lead to instability and a rise in torque ripples. Lower voltage levels can also amplify the effects of inverter non-linearity, like voltage and current harmonics, which can further affect the characteristics of torque ripple [6]-[8].

Controlling the voltage levels applied to the motor windings is a critical function of inverter modulation techniques like pulse-width modulation (PWM) [9]. The torque ripple characteristics are determined by the modulation strategy, which also controls the duty cycle, switching frequency, and voltage waveform shape. Sophisticated modulation algorithms optimize voltage waveforms taking into account the electrical and

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mechanical dynamics of the motor in an effort to minimize torque ripple [10]-[11]. The torque ripple analysis is further complicated by the interplay between inverter voltage levels and motor control techniques like direct torque control (DTC) and field-oriented control (FOC) [13]. Since different control algorithms react differently to inverter voltage levels, it is important to fully comprehend how these algorithms interact in order to minimize torque ripple. In conclusion, one of the most important aspects of motor drive design and optimization is the impact of inverter voltage levels on torque ripples of PMSM drives [14]. It takes careful consideration of a number of factors, including inverter modulation techniques, control algorithms, and operating conditions, to balance voltage levels to achieve smooth torque output while minimizing losses and avoiding motor saturation. Resolving these issues can improve overall system efficiency, minimize vibration, and improve motor performance [15]-[16].

A permanent magnet synchronous motor will not produce torque ripples when it fed from direct clean sinusoidal voltage source. However, the switching of power electronic devices produces harmonics in the motor voltages and hence currents which will result in torque ripple. The main objective of this work is to identify a suitable scheme to reduce the ripples / harmonics in stator currents. Multilevel inverter is chosen as oner of the available methods in reducing the torque ripples from the literature. Different voltage levels are impressed on the motor winding with multilevel inverter and observing the current ripples / flux ripples is the primary goal of this work.

2 Mathematical Model of Permanent Magnet Synchronous Motor

The equivalent circuits of the Induction motor and the synchronous motor are almost similar. The production of rotating magnetic field from the three-phase stator winding is same in both the motors even constructional wise. In PMSM, the induction motor's rotor parameters are replaced with an independent flux constant which represents the permanent magnet of the machine. The speed voltage's role will be as usual on the stator. Using Clarke's transformation, the three phase ABC parameters are transformed to alpha beta parameters. The αβ model – stator voltage equation is given below.

$$\begin{bmatrix}V_\alpha\\ V_\beta\end{bmatrix} = \begin{bmatrix} r_s & 0\\ 0 & r_s\end{bmatrix}\begin{bmatrix}i_\alpha\\ i_\beta\end{bmatrix} + \begin{bmatrix}L_{ls}+\frac{3}{2}L_{ms} & 0\\ 0 & L_{ls}+\frac{3}{2}L_{ms}\end{bmatrix}\begin{bmatrix}pi_\alpha\\ pi_\beta\end{bmatrix} + \lambda_m \frac{d\theta_r}{dt}\begin{bmatrix}-sin(\theta_r)\\ cos(\theta_r)\end{bmatrix} ---------- (1)$$

$$T_e = P\lambda_m\left(i_\beta\, cos(\theta_r) - i_\alpha\, sin(\theta_r)\right) ---------------------------(2)$$

Similarly, the torque dependencies are also shown below. The equation is developed using Park's transformation.

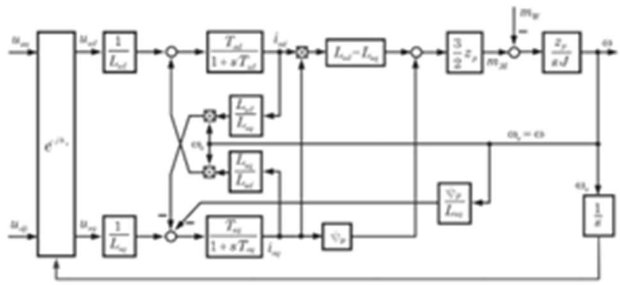


Fig. 1. Equivalent Circuit of PMSM

$$V_d = R_s i_d + \frac{d}{dt}\psi_d - \omega_r \omega_q$$
$$V_q = R_s i_q + \frac{d}{dt}\psi_q + \omega_r \omega_d \quad (3)$$
$$\psi_d = R_s i_q + \psi_{pm}$$
$$\psi_q = L_q i_q$$
$$T = \frac{3}{2}P[(L_d - L_q)i_d i_q + \psi_{pm} i_q] \quad (4)$$

3 Diode Clamped Multilevel Inverter

The figure below depicts the simplified circuit diagram of a three-level diode-clamped multilevel inverter. We require (m-1) number of capacitors, [2(m-1)] number of switching devices, and [(m-1) (m-2)] number of clamping diodes for each leg for the three levels. Four active switches and four anti-parallel diodes make up each inverter leg.

Two capacitors, designated Cd1 and Cd2, split the input voltage Vd into two portions. Cd2 supplies the neutral point, or Z. The two clamping diodes that are utilised to manage the reverse voltage are thus Dz1 and Dz2. Diodes are used to achieve different voltage levels at the output by passing different phases of series-connected capacitor banks through them. It is practically necessary for switches to have two-way power flow.

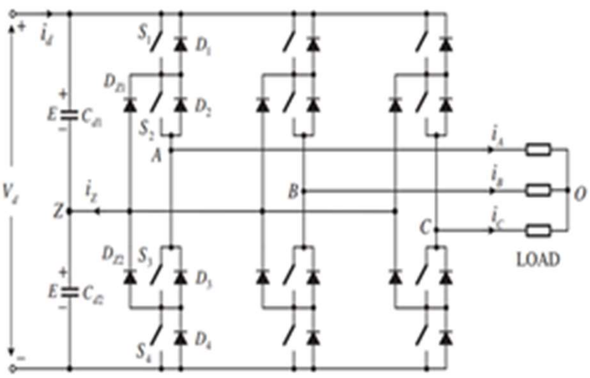


Fig. 2. Diode Clamed Multilevel Inverter

Table 1. Switching Sequence of The DCML Inverter

V_{ao}	S_1	S_2	S_3	S_4
$V_{dc/2}$	1	1	0	0
0	0	1	1	0
$-V_{dc/2}$	0	0	1	1

4 Simulation and Results

The diode clamped multilevel inverter was chosen for simulation to observe the effect of voltage levels on Torque ripples of PMSM drive. Three inverters – 2 level, 3 level and 5 level are designed and a PMSM – alpha beta model is used to study the three cases.

The electromagnetic torque, torque ripple, flux pattern, RMS stator current, Current wave THDs and Torque harmonics with respect to the DC component of the electromagnetic torque are obtained from the simulation.

The ripple factor percentage is recorded for a range of inverter reference frequencies and four load torque cases (25%, 50%, 75% and 100%). The Load torque applied to the machine is shown in Fig. 3.

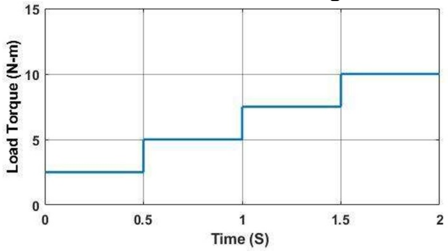


Fig. 3. Applied load torque (25%, 50%, 75% and 100% of rated Torque)

The electromagnetic torque for all the three inverters driving the similar PMSM motors are shown in Fig. 4.

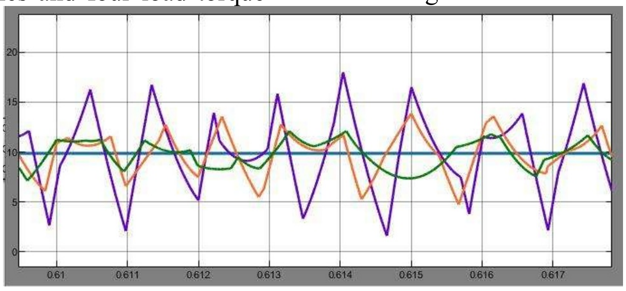
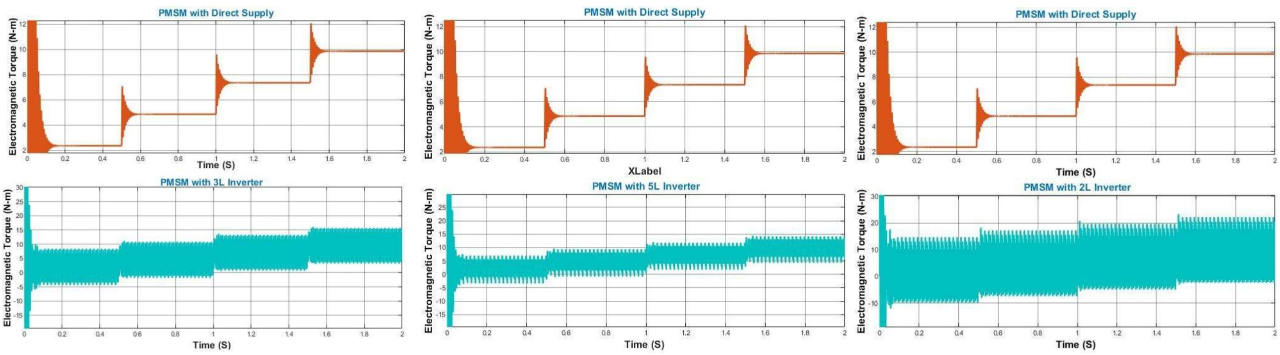


Fig. 4. Electromagnetic Torque comparison of PMSMs driven by 2L, 3L & 5L inverters



(i) (ii) (iii)

Fig. 5. Electromagnetic torque of PMSM driven with direct supply and multilevel inverters (i) 2L inverter fed PMSM torque compared to direct supply drive. (ii) 3L inverter fed PMSM torque compared to direct supply drive. (iii) 5L inverter fed PMSM torque compared to direct supply drive.

Fig. 5. Electromagnetic torque of PMSM driven with direct supply and multilevel inverters (i) 2L inverter fed PMSM torque compared to direct supply drive. (ii) 3L inverter fed PMSM torque compared to direct supply drive. (iii) 5L inverter fed PMSM torque compared to direct supply drive.

The torque profile is shown in Fig. 5. is captured at steady state. The machine connected to direct supply generates electromagnetic torque settled at 10 N-m. This is taken for the comparison with inverter driven cases. The maximum peak to peak electromagnetic torque for a 2 – level (2L) inverter is about 16 N-m, for a 3 – level (3L) is 8 N-m and for a 5 – level (5L) inverter is 5 N-m for 10 N-m applied load torque. The rated load torque 10 N-m is applied in periodic intervals to the PMSMs for all the three inverters. It is observed that the peak-to-peak torque ripple remains constant for all load cases. The torque ripples have been dropped as the number of levels is increased. It can be observed from Fig. 5 that, a drop of 50 % ripple in 3L inverter compared to 2L inverter. And in 5L inverter case, the torque ripple is dropped to 31%.

In this paper torque ripple calculation was done in two ways. In first method, the ripple was expressed as ripple factor by calculating the RMS torque and divide it with the average torque. The % of the calculated ratio is tabulated in the table 2. The stator flux components Øα and Øβ for direct supply and the three multilevel inverters are shown in Fig. 6. The stator current THDs were shown in Fig. 7 for all the three inverters.

Table 2. Torque Ripple Factor for The Inverters (2l, 3l & 5l) For Incremental Application of Load Torque

	Torque Ripple factor % (T_rms / T_avg)		
% of T_rated	**2L inverter**	**3L inverter**	**5L inverter**
25%	185	145	125
25%	125	110	105
25%	110	105	101
25%	105	101	100

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In the second method, the average torque is subtracted from the instantaneous electromagnetic torque. The result gives the torque ripples. The instantaneous torque samples are stored at a rate of (Tsw =) 10000 samples per second. The simulation is run for 2 seconds, and the total samples captured were 20000. The results were shown in Fig. 8. The simulation is done for 10 N-m load torque. In 2L inverter, it is observed that the torque was swinging between +15 N-m to -15 N-m for a 10N-m applied load torque. In 3L inverter, the torque swings between +8 N-m to -8 N-m and for 5L inverter, the limits are +4 N-m to -4 N-m. The comparison of the torque ripples for all the three inverters is shown in Fig. 9. The Torque spectrum of PMSM drive fed from direct supply and 2L, 3L, 5L inverters is shown in Fig, 10.

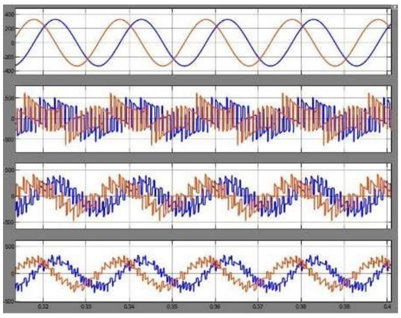

Fig. 6. Stator flux components Øα and Øβ of direct supply and 2L, 3L, 5L inverters

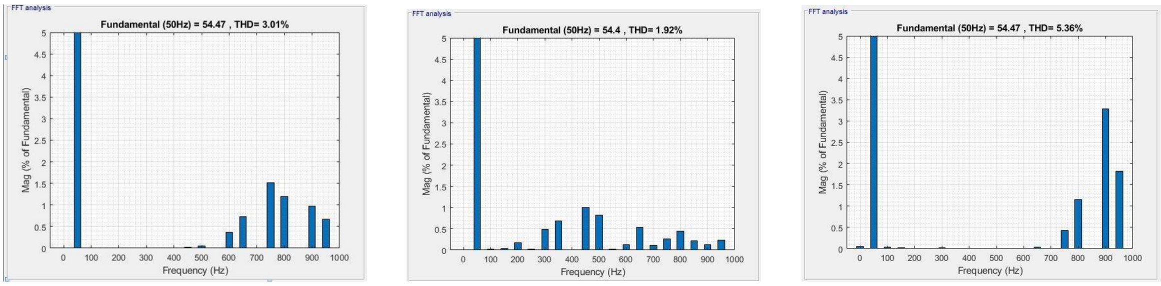

Fig. 7. THDs of stator currents of 2L, 3L and 5L inverters

Fig. 8. Torque ripple calculated using second method for 2L, 3L and 5L inverters

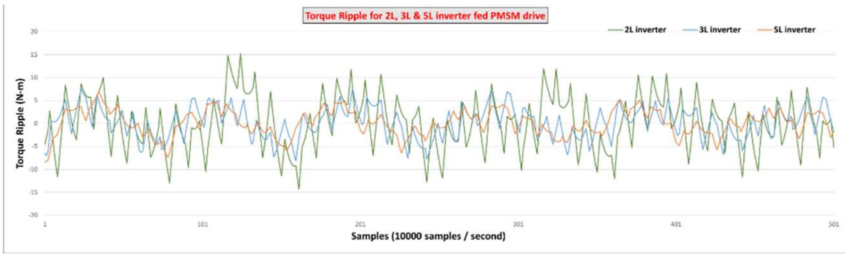

Fig. 9. The Torque ripples for 2L, 3L and 5L inverters

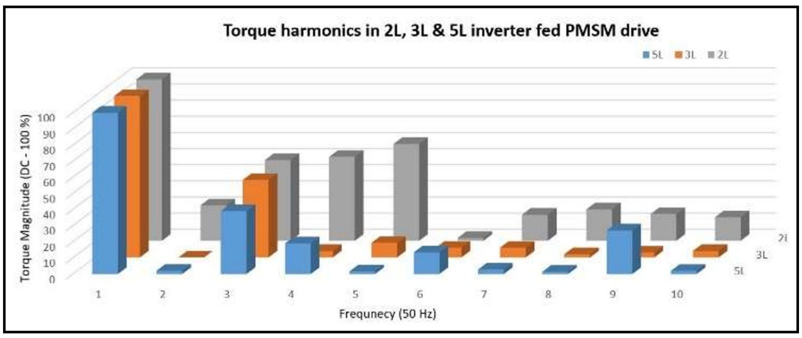

Fig. 10. Torque spectrum of PMSM drive fed from direct supply and 2L, 3L, 5L inverters

5 Conclusion

In conclusion, when designing and optimizing motor drives, the impact of inverter voltage levels on the torque ripples of Permanent Magnet Synchronous Motor (PMSM) drives must be taken into account. It is clear from this discussion that minimizing unwanted torque fluctuations and obtaining smooth torque output depend on striking the correct voltage level balance. Higher voltage levels enable smoother current waveforms and better motor control, which generally reduces torque ripples. To prevent negative effects on motor performance and reliability, however, the risks of increased losses, motor saturation, and thermal issues need to be carefully managed. On the other hand, lower voltage levels, especially when there is a high speed or heavy load, can result in instability and inadequate torque production. Furthermore, lower voltages may intensify the effects of inverter non-linearities, which may result in an increase in the characteristics of torque ripple.

To effectively mitigate torque ripples, a comprehensive strategy taking into account different aspects such as operating conditions, control algorithms, and inverter modulation techniques is needed. For the purpose of maximizing torque fluctuations and optimizing voltage waveforms, pulse-width modulation (PWM) techniques and sophisticated control algorithms are essential.

Ultimately, torque ripples in PMSM drives can be minimized through careful management of inverter voltage levels and the application of suitable modulation and control techniques. This results in better motor performance, decreased vibration, and increased system efficiency. To further enhance PMSM drives' capabilities in a range of industrial applications, more research and development in this field is imperative.

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