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Performance analysis of conventional multilevel inverter driven PMSM drive in EV applications

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ABSTRACT

This paper describes the simulation and hardware analysis of a two-level inverter-driven permanent magnet synchronous motor (PMSM) drive in EV applications. The design of various sections of PMSM Drive is discussed in detail. This proposed work is based on the voltage source converter (VSC) fed four-pole, 373 W. This paper highlights the design and implementation using a microcontroller of (PMSM) drive for various operating conditions. The experimental results show that the control and power circuit used in the design can achieve excellent and consistent speed performance. The performance along with test results of the speed and load variation of the PMSM drive is studied for steady-state conditions. The performance of the motor has been checked by increasing the inverter frequency with the speed of the motor and also keeping the frequency remains constant by varying the load and speed. Hardware analysis indicates the improved performance of the motor and the drive. It has good speed and torque responses and is suitable for EPS applications.

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1. INTRODUCTION

The low value of cogging torque, ruggedness, high efficiency, high power-to-weight ratio, and additional reluctance torque are the permanent magnet synchronous motor (PMSM) characteristics. Hence it is used in electric vehicle applications due to the motor running to different load and speed profiles. It is not needed to supply magnetizing currents through the stator flux due to the magnet in the rotor and the constant air gap in PMSM. This paper focuses on low speeds and the back emf respectively. When at high speed, it gives high current and less switching losses. It would operate at low and high switching frequencies for low and high speeds respectively [1]-[7].

This paper explains the performance analysis of VSI-driven SVM-PMSM drives for EV applications. Voltage source inverter-driven PMSM drive is one of the widely used methods for speed and torque control [8]-[14]. Three three-phase rectifier circuits give the fixed DC voltage. The shunt capacitor is used for filter purposes. The output transfer to MOSFET bridge inverters [15]-[20]. For getting pulses, the control circuit is used and an isolator and driver circuit is used for isolation [21]-[25].

The theme of the paper is the design of conventional inverter-driven PMSM drives in EPS applications. Sections 1 and 2 describe the introduction and mathematical model of PMSM, section 3 describes the simulation model and analysis, and section 4 describes design considerations. Sections 5 and 6 present experimental results and conclusion respectively.

2. MATHEMATICAL MODEL OF PMSM

2.1. Rotor reference frame PMSM

The modelling of the PMSM machine has been presented henceforth in the rotor reference frame. In a PMSM, the rotor is a permanent magnet without any windings and hence there are no equations associated with the rotor. The 3-φ stationary ‘abc’ frame can be transformed into 2-φ synchronously rotating ‘dq’ frame, with the help of abc → dq transformations. In the ‘dq’ frame, the stator has two windings: d-axis winding and q-axis winding; and the d-axis winding is aligned with the magnetic pole axis. Consider the PMSM machine running at the speed of ‘ωr’, in the anti-clockwise direction. The D-axis induced voltage is (1).

$$u_d = R_d i_d + \frac{d\lambda_d}{dt} - \omega_r \lambda_q \tag{1}$$

The Q-axis induced voltage is shown in (2)-(5).

$$u_q = R_q i_q + \frac{d\lambda_q}{dt} - \omega_r \lambda_d \tag{2}$$

$$\lambda_d = L_d i_d + \lambda_m \tag{3}$$

$$\lambda_d = L_{qiq} \tag{4}$$

$$L_d = L_q \tag{5}$$

The torque equation is (6).

$$T_e = \frac{3}{2}\frac{\mathrm{p}}{2}(\lambda_\mathrm{d} i_q - \lambda_\mathrm{q} i_d) \tag{6}$$

Put in (7).

$$T_e = \frac{3}{2}\frac{\mathrm{p}}{2}[(\lambda_\mathrm{d} i_d + \lambda_m) i_q - \mathrm{L_q} i_q i_d] \tag{7}$$

$$T_e = \frac{3}{2}\frac{\mathrm{p}}{2}[(\mathrm{L_d} - L_q) i_d i_q + \lambda_m i_q] \tag{8}$$

$$Reluctance\ torque = \frac{3}{2}\frac{\mathrm{p}}{2}(\mathrm{L_d} - L_q) i_d i_q \tag{9}$$

$$field\ torque = \frac{3}{2}\frac{\mathrm{p}}{2}\lambda_m i_q \tag{10}$$

$$T_e = \frac{3}{2}\frac{\mathrm{p}}{2}\lambda_m i_q \tag{11}$$

Hence the electromagnetic torque present in a round rotor permanent magnet synchronous machine is nothing but the field torque which is present due to the permanent magnet flux linkage, *λm*. For a chosen permanent magnet synchronous machine, the number of poles (*p*) is constant as well as the permanent magnet rotor flux-linkage *(λm)*. Hence, the electromagnetic torque equation for the round-rotor PMSM can be rewritten as (12) and (13).

$$\mathrm{Te=Ktiq} \tag{12}$$

$$K_t = \frac{3}{2}\frac{\mathrm{p}}{2}\lambda_m \tag{13}$$

Therefore, electromagnetic torque is (14).

$$T_e = T_l + B\,\omega_m + J\,\frac{d\omega_m}{dt} \qquad (14)$$

3. SIMULATION MODEL ANALYSIS

Figure 1 shows the Simulink model of a two-level inverter-driven PMSM drive. Figures 2-4 show motor response at 280 rpm, 500 rpm, and 1500 rpm. Figure 5 shows a fast Fourier transform (FFT) analysis of a two-level inverter-driven PMSM drive. Table 1 shows the torque ripple analysis of a two-level inverter. In Figure 2, at 0.01 sec, load torque 3 N-m is applied and removed at 0.03 sec. The torque varies with the load The reference speed is 500 rpm and the fluctuation in speed on removal of torque than speed remains constant. Speed, three-phase stator current, and electromagnetic torque are constant with some ripples at 0.6 sec.

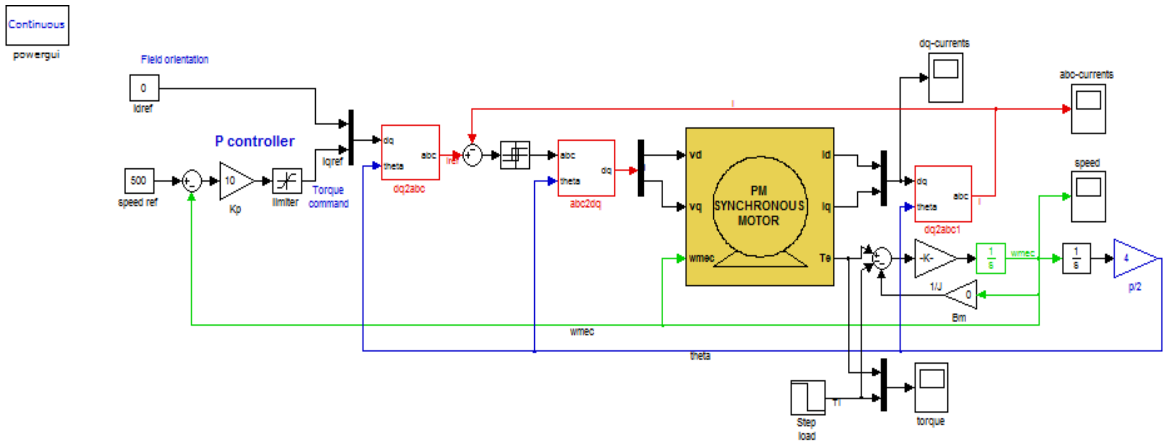

Figure 1. Simulink model of two-level inverter-driven PMSM drive

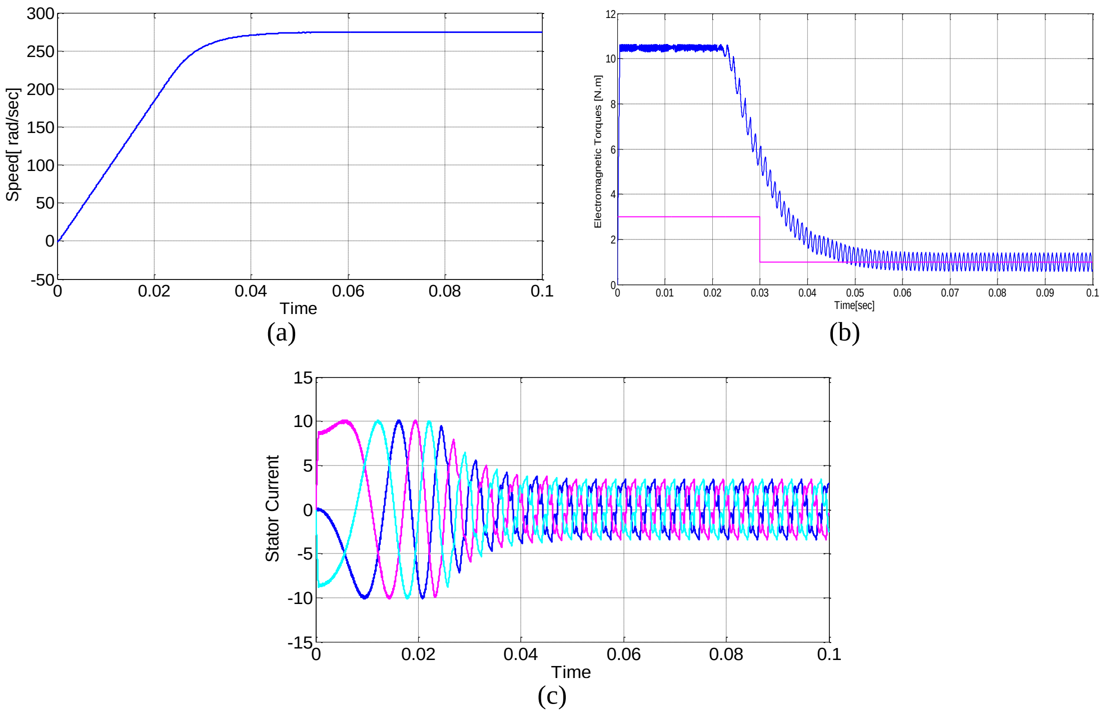

Figure 2. Motor response at 280 rpm (a) rotor speed, (b) electromagnetic torque, and (c) three-phase stator current

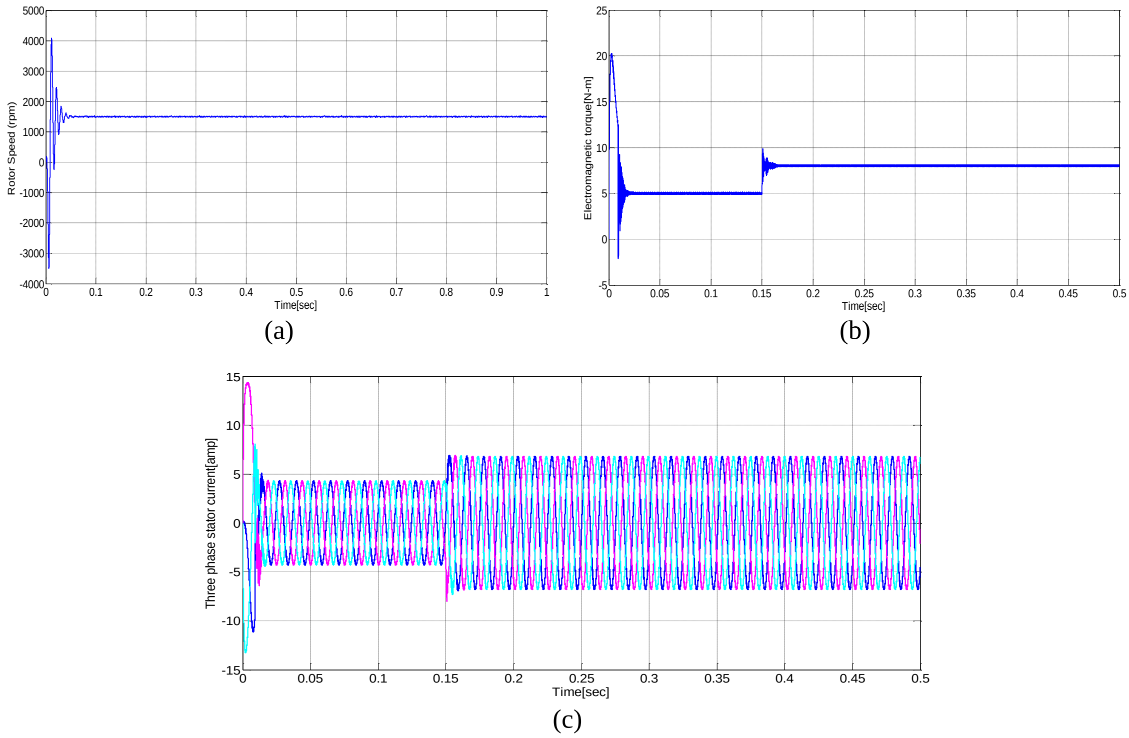

Figure 3. Motor response at 500 rpm (a) rotor speed, (b) torque, and (c) three-phase stator current

In Figure 3, at 0.01 sec, load torque 3 N-m is applied and removed at 0.15 sec. The torque varies with the load The reference speed is 500 rpm and the fluctuation in speed on removal of torque than speed remains constant. Speed, three-phase stator current, and electromagnetic torque are constant with some ripples at 0.15. The torque varies with the load The reference speed is 500 rpm and the fluctuation in speed on removal of torque than speed remains constant. Speed, three-phase stator current, and electromagnetic torque are constant with some ripples at 0.06 sec.

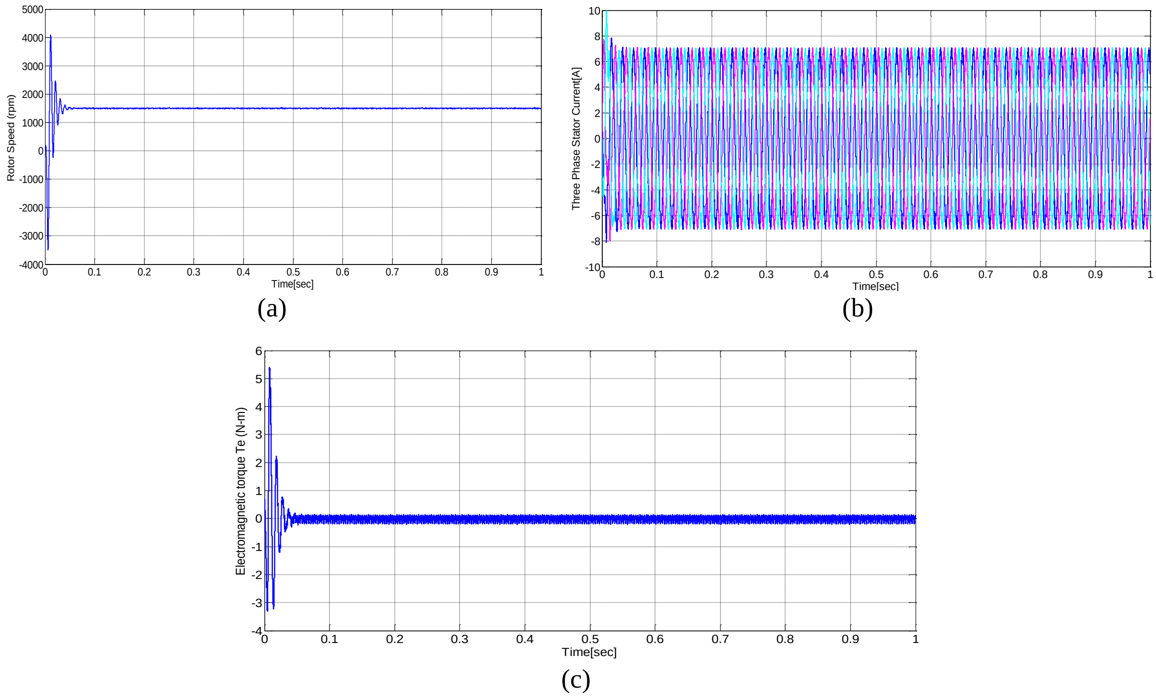

Figure 4. Motor response at 1500 rpm (a) rotor speed, (b) torque, and (c) three-phase stator current

In Figure 4, at 0.01 sec, load torque 5 N-m is applied and removed at 0.03 sec. The torque varies with the load the reference speed is 500 rpm and fluctuation in speed on removal of torque than speed remains constant. Speed, three-phase stator current, and electromagnetic torque are constant with some ripples at 0.06 sec.

Table 1. Torque ripples analysis (two level inverter)

Controller speed	% Torque ripples
280 rpm	21.98%
500 rpm	18.57%
1500 rpm	12.48%

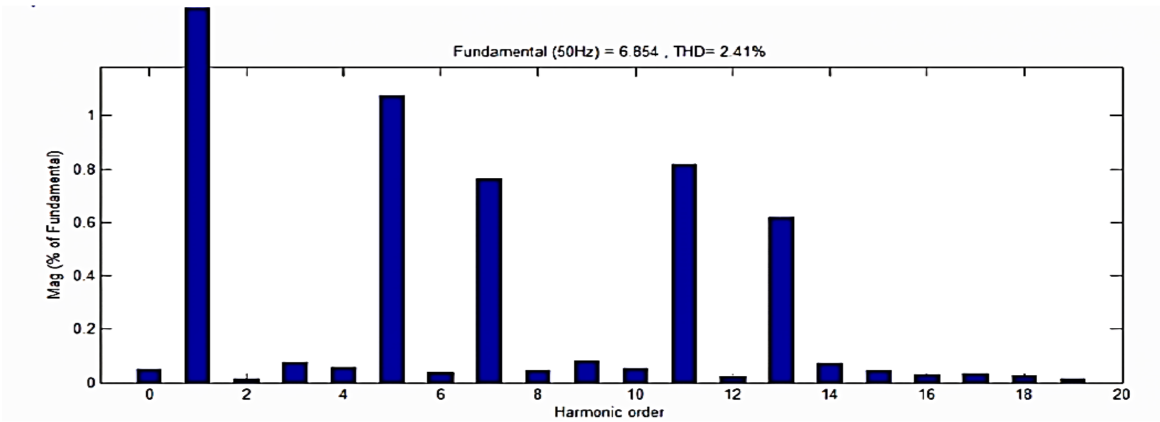

Figure 5. FFT analysis of two-level inverter-driven PMSM drive

4. EXPERIMENTAL RESULTS ANALYSIS

Figure 6 shows the block diagram of the PMSM drive. Figure 7 shows the output voltage and capacitor voltage waveform. Figure 8 shows the gate pulse pattern for the MOSFET. Table 2 shows motor speed variation by frequency. Tables 3-5 show motor speed variation by load at 30, 40 Hz, and 50 Hz. Figure 7 shows speed-frequency characteristics. Figure 8, Figure 9, and Figure 10 shows load-speed characteristics at 30 Hz, 40 Hz, and 50 Hz.

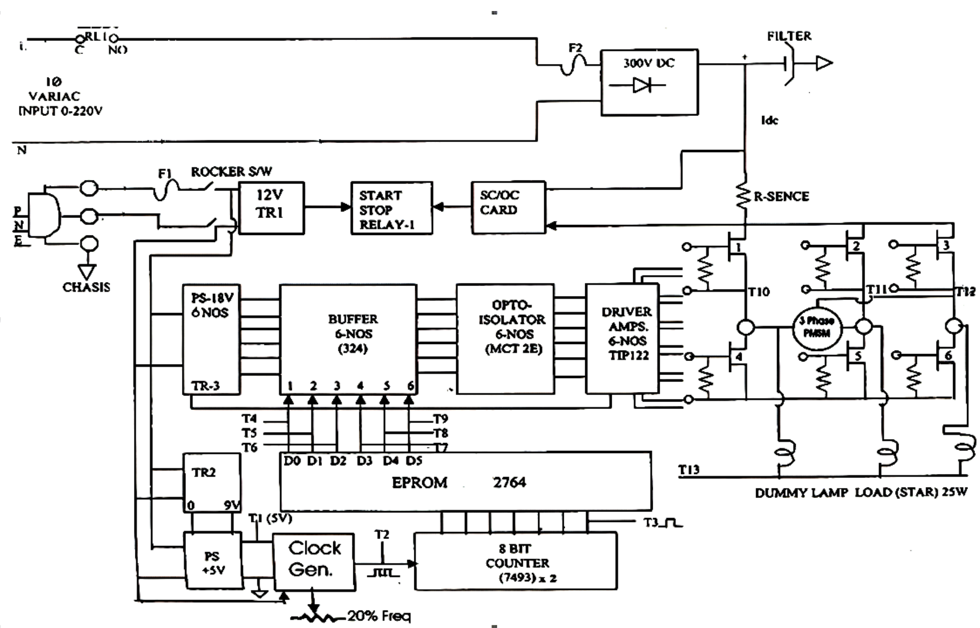

Figure 6. Block diagram of the PMSM drive

Table 2. Motor parameter frequency variation

Sr. No.	Time	Frequency	Actual speed	Measured Speed	Voltage
1	0.033 m.s	30 Hz	900 rpm	950 rpm	240 V
2	0.025 m.s	40 Hz	1200 rpm	1210 rpm	240 V
3	0.02 m.s	50 Hz	1500 rpm	1490 rpm	240 V
4	0.05 m.s	60 Hz	1800 rpm	1790 rpm	240 V

Table 3. Motor parameter load variation (30 Hz)

Sr. No.	Weight	Frequency	Motor Speed	Motor Speed	Motor Torque	Motor Power
1	500 gm	30 Hz	900 rpm	950 rpm	0.12 N-m	14.20 W
2	1000 gm	30 Hz	900 rpm	950 rpm	0.22 N-m	34.78 W
3	1500 gm	30 Hz	900 rpm	950 rpm	0.35 N-m	42.48 W
4	2000 gm	30 Hz	900 rpm	950 rpm	0.56 N-m	62.47 W
5	2500 gm	30 Hz	900 rpm	950 rpm	0.78 N-m	72.02 W
6	3000 gm	30 Hz	900 rpm	950 rpm	0.85 N-m	95.47 W

Table 4. Motor parameter load variation (40 Hz)

Sr. No.	Weight	Frequency	Motor Speed	Motor Speed	Motor Torque	Motor Power
1	500 gm	40 Hz	1200 rpm	1210 rpm	0.14 N-m	28.98 W
2	1000 gm	40 Hz	1200 rpm	1210 rpm	0.21 N-m	47.69 W
3	1500 gm	40 Hz	1200 rpm	1210 rpm	0.35 N-m	71.54 W
4	2000 gm	40 Hz	1200 rpm	1210 rpm	0.58 N-m	92.97 W
5	2500 gm	40 Hz	1200 rpm	1210 rpm	0.74 N-m	120.15 W
6	3000 gm	40 Hz	1200 rpm	1210 rpm	0.85 N-m	144.94 W

Table 5. Motor parameter load variation (50 Hz)

Sr. No.	Weight	Frequency	Motor Speed	Motor Speed	Motor Torque	Motor Power
1	500 gm	50 Hz	1510 rpm	1490 rpm	0.21 N-m	32.46 W
2	1000 gm	50 Hz	1510 rpm	1490 rpm	0.43 N-m	54.61 W
3	1500 gm	50 Hz	1510 rpm	1490 rpm	0.52 N-m	82.37 W
4	2000 gm	50 Hz	1510 rpm	1490 rpm	0.65 N-m	105.34 W
5	2500 gm	50 Hz	1510 rpm	1490 rpm	0.80 N-m	132.25 W
6	3000 gm	50 Hz	1510 rpm	1490 rpm	0.95 N-m	162.94 W

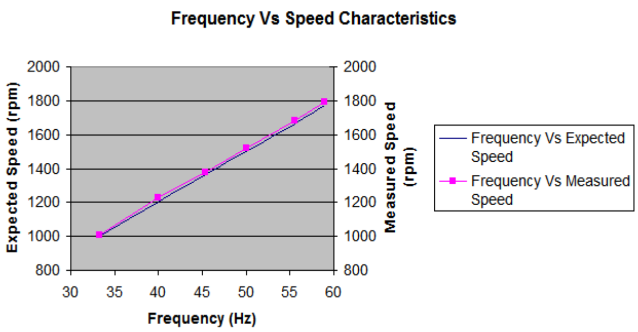

Figure 7. Motor speed characteristics at a frequency

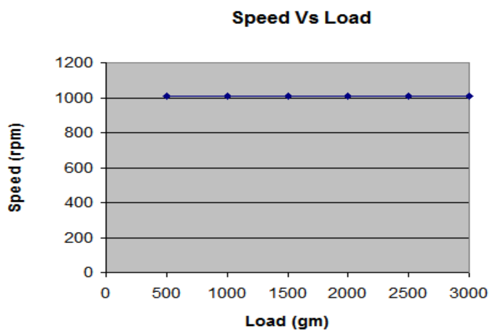

Figure 8. Motor characteristics at 33.3 Hz

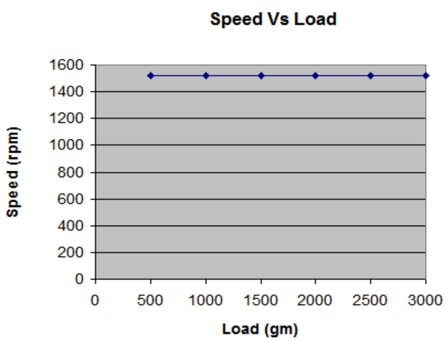

Figure 9. Motor characteristics at 50 Hz

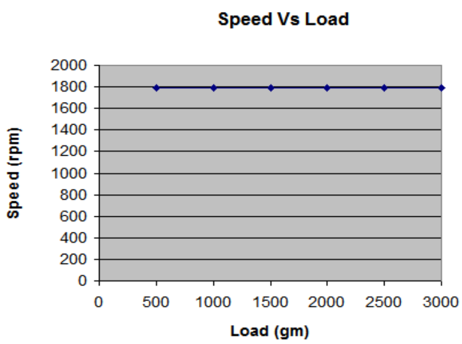

Figure 10. Motor characteristics at 59 Hz

5. CONCLUSION

This paper presentation a detailed Simulink model for performance analysis of conventional multilevel inverter driven PMSM drive in EV applications has being developed. It is shown in the experimental and simulation results of performance analysis of conventional multilevel inverter driven PMSM drive that the speed of the permanent magnet synchronous motor can be varied by varying the frequency of an inverter. Hence an attempt has been made to verify the performance of the motor. It is found that, speed remains constant at constant frequency, with varying load conditions and the test result shows the improved performance of the motor. In this paper simulation of permanent magnet synchronous motor gives constant torque in experimental and simulation results with less torque ripples and constant speed as shown in the above waveform and result tables. Hence this PMSM drive used in EPS application.

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