Modeling and Analysis of Three-Phase Inverter for Induction Motor Drive for Three-Wheel Electric Vehicle Application

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Abstract. This paper presents the control scheme Modeling and analysis of three phase voltage switching inverter in using Space vector Pulse Width Modulation (SVPWM) technique for induction motor driven three-wheel electric vehicles. Induction motors are now widely applied in electric vehicle industries as the replacement of internal combustion engine due to the over striking price and environmental concerns. Performance of speed, direction and torque control for three wheel electric drives (Bajaj) has been studied. Better dc utilization for medium performance drive system, more efficient use of DC supply voltage, produce less ripples makes space vector pulse width modulation technique a good choice for this work. By keeping the ratio of stator voltage to frequency constant, this system tipscan adjust the speed of the motor by control the frequency and amplitude of the stator voltage. Transfer model of induction motor, vehicle dynamic model and voltage source inverter type SVPWM model are designed and simulated using matlab Simulink. Control scheme visual realization has been done though Protues and Arduino IDE software. To demonstrate good performance of SVPWM based induction motor for three wheel drive, parameters such has stator current, rotor current, torque and speed as well as switching patter of the inverter waveforms have been displayed and analyzed.

Keywords: SVPWM · Induction motor · Voltage source inverter · Three-wheel electric vehicles · MATLAB/SIMULINK

1 Introduction

Induction Machines is the most widely used motor in industry and also in residential application. Its low cost, high efficiency, wide speed range and robustness makes induction motors to be applied in various applications. Now a day, in the most of the industrial applications, due to their simple and most tough construction without any mechanical commentator, AC motors are more useful than DC machines [1, 2].

In EVs propulsion, three phase AC induction motor drive is fed from three phase inverter with a DC source or battery at approximately constant voltage, through a DC/AC

M. A. Delele et al. (Eds.): ICAST 2020, LNICST 384, pp. 170–183, 2021.
https://doi.org/10.1007/978-3-030-80621-7_13

inverter [3]. The DC/AC inverter is constituted by a fast switching power electronic switches and power diodes. IGBTs and MOSFETs are commonly used in the inverters configurations. A high speed processor in order to produce the proper switching sequence is needed since AC voltage output of the inverter has high frequency square wave forms.

To determine the amplitude and the frequency of the output voltage, various switching schemes are used to generate PWM signal. Space Vector Pulse Width Modulation (SVPWM) one of the various PWM techniques that best suits for electric vehicle application [4].This type of modulation has the following interesting features such as offers better DC-link utilization, more efficient use of DC source voltage, yield less ripples and improved life time of drive [5].

The paper is structured as follows: first system description is discussed, second modeling part is presented, and third power and control issues are demonstrated and finally results obtained are presented along with conclusions.

2 System Descriptions

This paper work consists of the source, the three-phase inverter, the three-phase induction motor, three wheel vehicle (Bajaj) and the Arduino microcontroller. Generally, this proposed system is illustrated in the following Fig. 1. Three phase IGBT based inverter, fed from dc source/battery, converts DC to AC voltage to power three phase induction motor as described in Fig. 1. The controller will generate the pulse width modulation (PWM) to feed the inverter using Arduino and amplified through gate drive circuit.

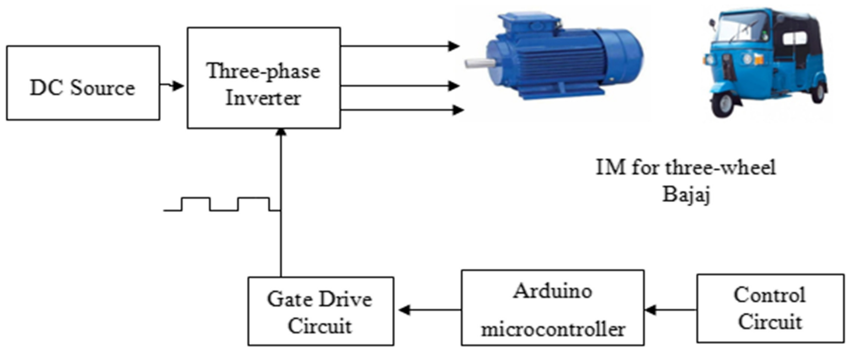

Fig. 1. Block diagram of the paper

The objective of this work is to model and analyze three phase inverter and its controller, Space Vector PWM, using Matlab and Protues with Arduino IDE software.

3 System Modeling and Simulation

3.1 Electric Vehicle Dynamics

Motor rated speed; motor power rating and Maximum speed of the motor are parameters to be considered in designing Electric vehicles [10].

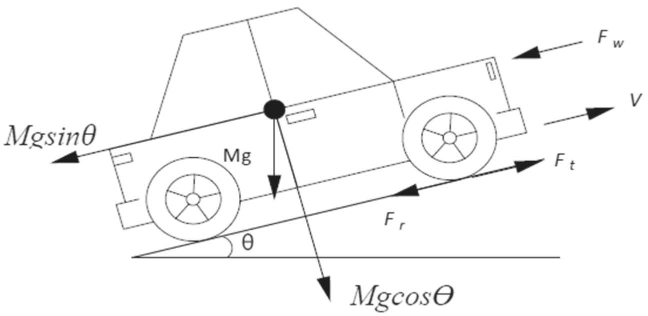

Fig. 2. Forces acting on electric vehicle

Road load is among several forces acting on vehicle while travelling that the vehicle to overcome [6] as shown in Fig. 2. This road load F_l consist of four components drag aerodynamic force F_d, rolling resistance force F_r, gradient or Clamping force F_c and acceleration resistance F_a,

$$F_r + F_d + F_c + F_a \tag{1}$$

Rolling Resistance: Rolling resistance of the tire, the resistive force of vehicle which opposes the rolling of the wheels, is given by:

$$F_r = C_{rr} * M * g * \cos(\theta) \tag{2}$$

where, C_{rr}: rolling resistance Coefficient, $(M * g)$: Vehicle load in N and θ: Inclination angle.

The power (Pr) required to overpowering the rolling resistance is calculated as

$$P_r = F_r * v\left(\frac{m}{sec}\right) \tag{3}$$

Gradient (Climbing) Resistance: The force that tends to pull the vehicle back, gradient resistance, when it is up hilling an inclined surface is given by:

$$F_c = M * g * \sin(\theta) \tag{4}$$

And the climbing power of the Bajaj is given by $P_C = F_C{*}V_C$.Where $V_c = V_{max}/2$ and v_c is the climbing velocity.

Aerodynamic Drag Force: The force acting on the vehicle body when it is travelling through air, the aerodynamic drag force which consists of the skin friction drags due to air flow in the boundary layer, normal pressure drags depends on the vehicle frontal area and speed and induced drag [5] is expressed by

$$F_d = \frac{1}{2} * V^2 * C_d * A * \rho \tag{5}$$

where,
C_d- the aerodynamic drag coefficient (lies between 0.2 and 1.5),
ρ -the air density in $kg/m^3 = 1.23$ kg/m,
V -the sum of speed of vehicle and speed of air in m/s.
A is frontal area of the plat form $A = 0.58 * 0.92 = 0.5336\ m^2$.
The total power required to drive the Bajaj is given by: $P_t = P_r + P_a + P_c + P_d$
Therefore, the mechanical power output necessary for driving the wheel including transmission losses on the wheel is given by the equation:

$$M_{peak} = \frac{P_{max}}{\text{efficiency of gear}} \tag{6}$$

To obtain the desired drive characteristics it is important to find the torque on the drive wheel using the following expression:

$$T = F_t \times \frac{r}{G} \tag{7}$$

Where, T is torque, r is radius of drive wheel and G is gear ratio.

For the calculation of tractive force, total tractive power and total tractive torque needed, at the wheel of the vehicle, the following parameters of the vehicle listed in the Table 1 are considered. To estimate the motor losses and efficiency, the following induction motor parameters shown in the Table 2 are considered.

Table 1. Electric Bajaj specification.

Parameter	Symbol	Value
Maximum power	P	7.52kw
Wheel base	B	1980mm
Total length	L	3030mm
Total width	W	1500mm
Total height	H	1780mm
Coefficient of rolling friction	C_{rr}	0.01
Vehicle mass	m	700 Kg
Air density	ρ	1.23 Kg/m3
Frontal area	A	0.35m2
Aerodynamic drag coefficient	Cd	0.2
Tire radius	R	0.1m
Gravitational acceleration	g	9.81m/s2

3.2 Space Vector Pulse width Modulation

In EVs propulsion, three phase AC induction motor drive is fed from three phase inverter with a DC source or battery at approximately constant voltage through a DC/AC inverter

Table 2. Induction motor specification.

Parameter	Value
Pole	4
Power	8KW
Efficiency	89.5%
Speed	1500-2000RPM
Frequency	50Hz
Slip	2.5%
Voltage	440V
Power factor	0.89
Moment of inertia	0.02
Full load Torque	52.6

with a fast switching power electronic switches and power diodes [3]. Space Vector Pulse Width Modulation (SVPWM), was originally developed as vector approach to Pulse Width Modulation (PWM) scheme for three phase inverters, one of the various PWM techniques that best suits for electric vehicle application [4].It is a more advanced technique with the following merits such as Minimization of harmonics, Minimization switching loss, Maximization of fundamental component, Utilization of DC voltage [3, 4, 7]. The existence of additional zero voltage states such asV0 (000), and V7 (111) is the difference between SVPWM and SPWM in addition to the six possible voltage vectors applied in VSI.

Thus, SVPWM is as an eight state operation with 6 operational vectors as shown in Fig. 3 below [8].

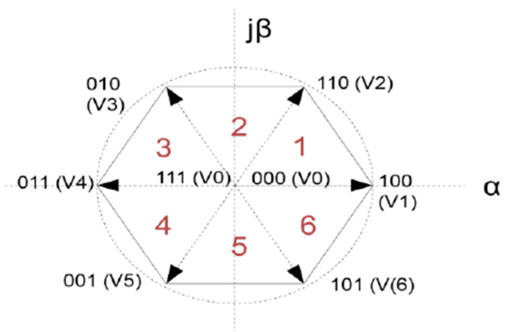

Fig. 3. Space voltage vectors in different sectors

3.3 Three Phases to Two Phase Transformation

The dynamic model of induction motor is studied by driving the equivalency of the transformation from three-phase to two-phase machine. The equivalence is based on the amount of MMF produced in two-phase and three-phase windings as well as equal current amounts. Assuming that each of the three-phase windings have Ns turns per phase and equal currents magnitudes, the two-phase winding will have $3N_s/2$ turns per phase for MMF equality. The direct (d) and Quadrature (q) axes MMF are resolved by using MMF of the three-phase along d and q axes.

The stator voltages of three-phase induction machine under balanced conditions is given by

$$V_a = \sqrt{2}V_{rms}\sin(\omega t) \tag{8}$$

$$V_b = \sqrt{2}V_{rms}\sin(\omega t - 120) \tag{9}$$

$$V_c = \sqrt{2}V_{rms}\sin(\omega t + 120) \tag{10}$$

Where V_a, V_b and V_c are the three line voltages,

The relationship between alpha beta(α_β) and abc is as follows

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{11}$$

Then, the direct and quadrature axes voltages are: -

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{12}$$

The instantaneous values of the stator and rotor currents in three-phase system are ultimately calculated using the following transformation;

$$\begin{bmatrix} i_a \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{13}$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{2}{3}\begin{bmatrix} -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_\beta \end{bmatrix} \tag{14}$$

3.4 MATLAB/SIMULINK Model

The simulation results are given for the induction motor for the following specification [6] (Table 3):

Table 3. Induction motor specifications

No	parameters	values
1	Number of poles [P]	4
2	Frequency [F]	50 Hz
3	Number of phases	3
4	Stator resistance [Rs]	1.115 ohms
5	Rotor resistance [Rr]	1.083 ohms
6	Stator inductance [Ls]	0.00597H
7	Mutual inductance [Lm]	0.2037 H
8	Moment of inertia [J]	0. 02 Kg-m/sec

Figure 4 describes the overall simulation of the system as shown below.

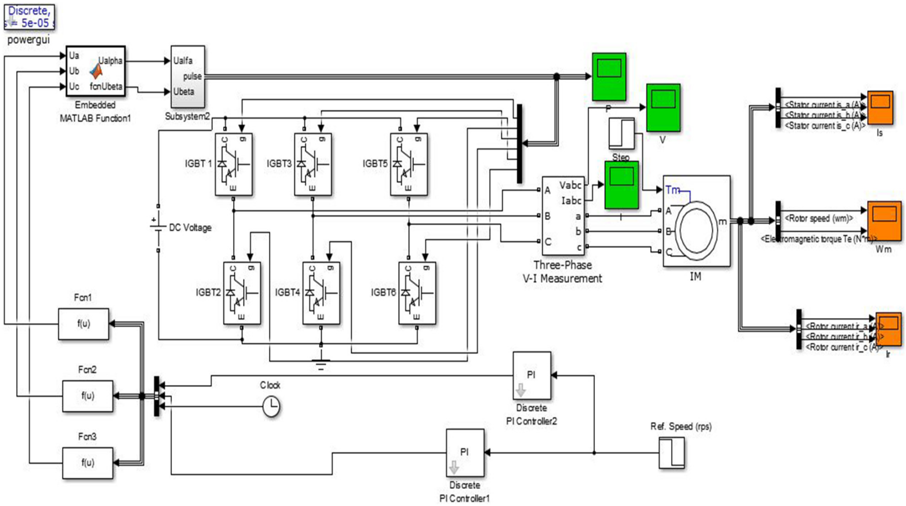

Fig. 4. MATLAB open loop Simulink model of SVPWM based induction motor

3.5 Proteus Simulation

Six IGBT, 4PC40UD, switches is used for the system that are turned on and off by pulse width modulation. The turn on and off of the IGBTs give rise to three phase output from dc source. These are high speed switching devices that turn on and turn off by sequence to produce three phase output. The inverter is simulated and switching of inverter is indicated with LEDs. The switching with LED positions is shown as in Fig. 5 below.

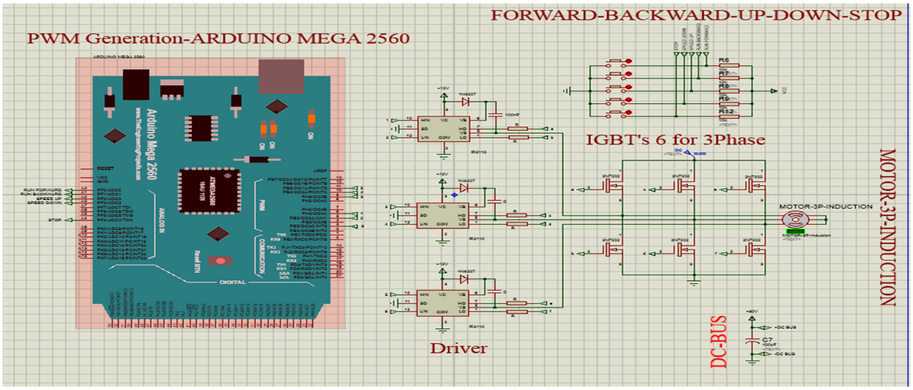

Fig. 5. Inverter with switching sequence

4 Results and Discussions

Switching Pattern of SVPWM Inverter: Figure 6 demonstrated that reduction of the heat of switches by reducing the switching ratio based on carrier. This pattern when compared to high frequency triangular carrier wave produces gating signal to drive the inverter. Because of common mode element in SVPWM compared to SPWM, there is an extra improvement in voltage compared with sinusoidal PWM as clearly indicated.

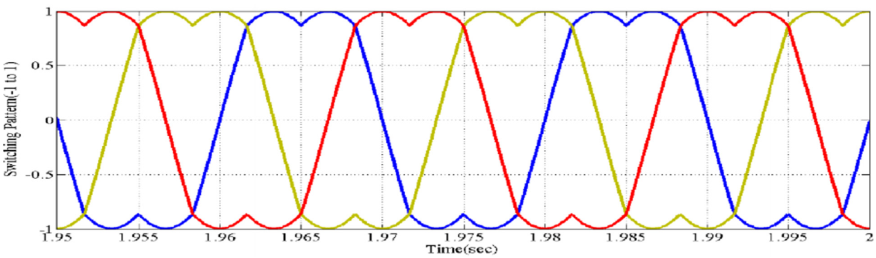

Fig. 6. Switching pattern of SVPWM inverters

Gate Pulse: The output get signal generated based on SVPWM techniques to switching the IGBT sequentially is shown in the Fig. 7, below. The signal that generated from the driver circuit is out phase in one leg. Because in one leg the two switches are on simultaneously a short circuit is happen and cause damage on the inverter. Thus, in order to generate three phase sinusoidal waves the switches are on and off sequentially based on the pattern of sector vectors.

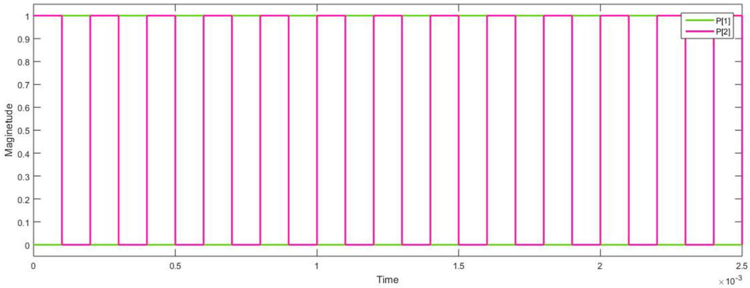

Fig. 7. Gate pulse for IGBT 1 and IGBT 2

Stator Current: The current in that flows through the stator winding of induction motor is shown in Fig. 8. Appropriate control algorithm is applied for motor depending on mechanical load torque so that the stator current should decrease the controller will supply stator with proper voltage and frequency.

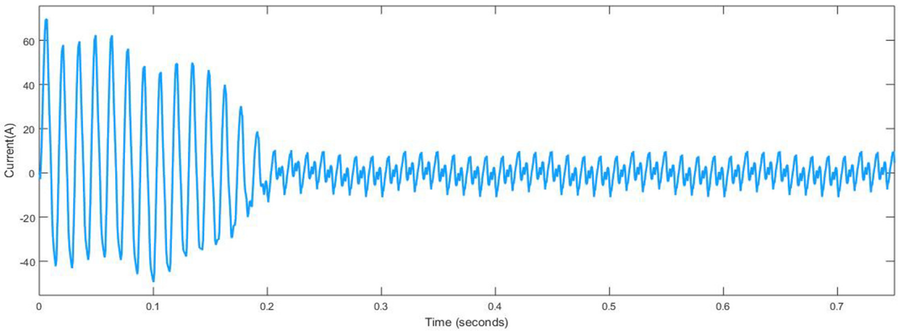

Fig. 8. Stator current

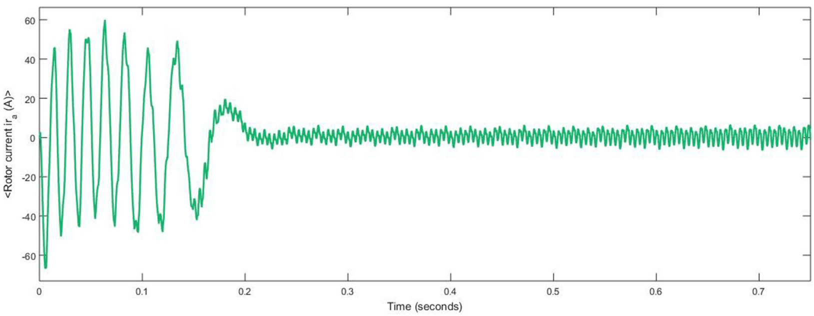

Fig. 9. Rotor current

Rotor Current: The current in the rotor winding of the induction motor is high in the starting. But as the motor accelerates current decreases. The drive automatically decreases the voltage after the motor is smoothly driven (Fig. 9).

Torque: Figure 10 demonstrated that the torque associated with induction motor is high because the starting torque of the induction motor. The torque required by the Bajaj is 52 Nm. After the motor rotate and start drive the vehicle, the torque comes to zero at reduced losses.

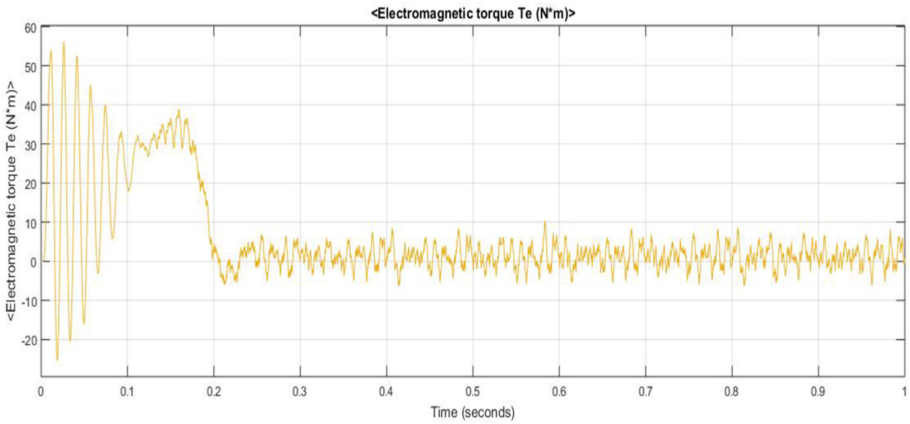

Fig. 10. Electromagnetic torque

The Torque-Speed Curve (At 50 Hz): The combined speed (X-axis) and torque (Y-axis) curve are shown in Fig. 11. The motor is operating at 50 Hz frequency. The speed and torque at 10 Hz are shown below these values are less than initially calculated at 50 Hz.

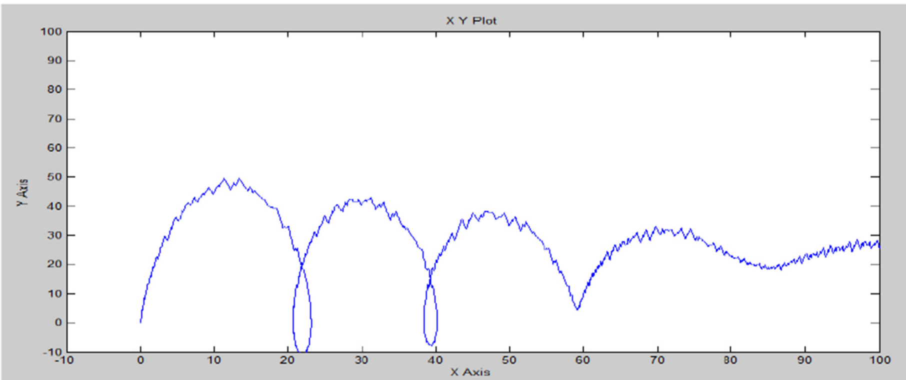

Fig. 11. Torque speed curve at 50 Hz

The Torque-Speed Curve (At 10 Hz): The toque speed curve of induction motor at 10Hz is represented as in shown in Fig. 12. The figure described that the cause reduction magnitude of torque- speed curve is the increase in switching time due to the minimized frequency.

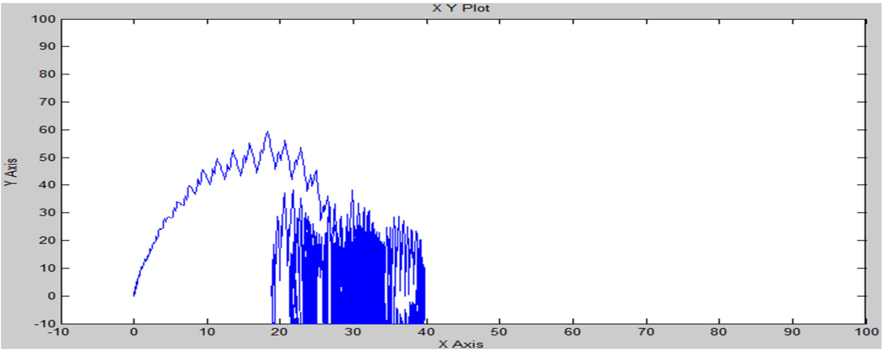

Fig. 12. Torque speed curve at 10 Hz

Motive Force Verses Approaching Angle of Vehicles: There are three main forces which act on the Bajaj when it travels at constant speed. Gradient force increases when the approaching angle is increase. Aerodynamics force is constant at constant speed of the vehicle. The total motive force with each component of the force acting on the vehicle is shown on the Fig. 13. We assumed the vehicle speed when move up is 25 km/h and velocity of the air also assumed equals to zero.

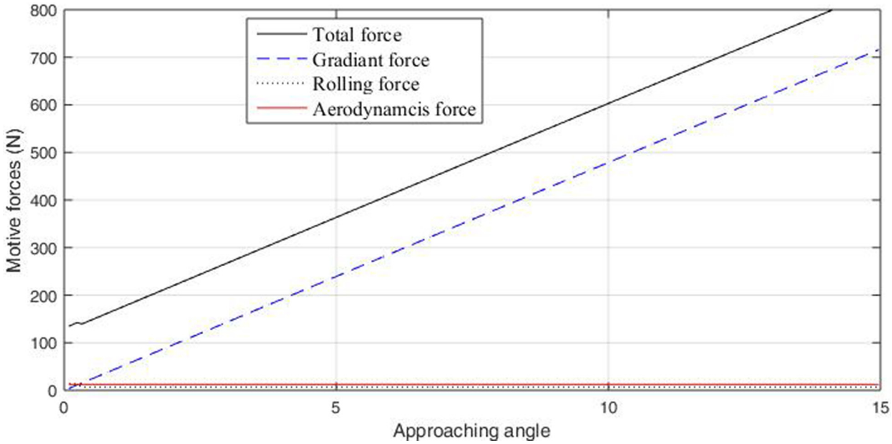

Fig. 13. Motive force verses approaching angle

Motor Power Consumption with Respect to Approaching Angle: The maximum reactive power is supplied when the Bajaj is clamping the hill of maximum approaching angle which is 7.67° at full load with the speed of 25 km/h . The speed of the Bajaj is reduced while clamping the hill is to increase torque with limited power output of the motor. Figure 14 show the power needed to be supplied by the motor to drive the Bajaj at constant speed of 25 km/h with verses approaching angle.

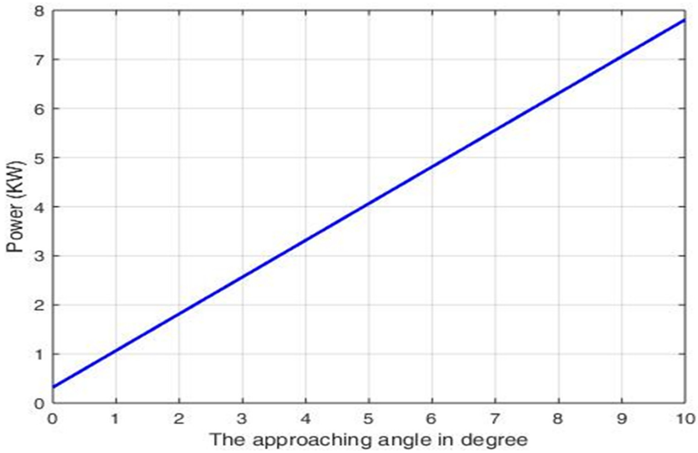

Fig. 14. Motor power consumption with respect to approaching angle

Forward and Reverse Direction Rotate of Motor: The push button in the control circuit is used to run the motor speed up, speed down, forward, reverse direction by due to the changing of switching pulse of IGBT gate signals. The following Fig. 15 and Fig. 16 shows that the output wave result when the motor run forward and reverse direction respectively.

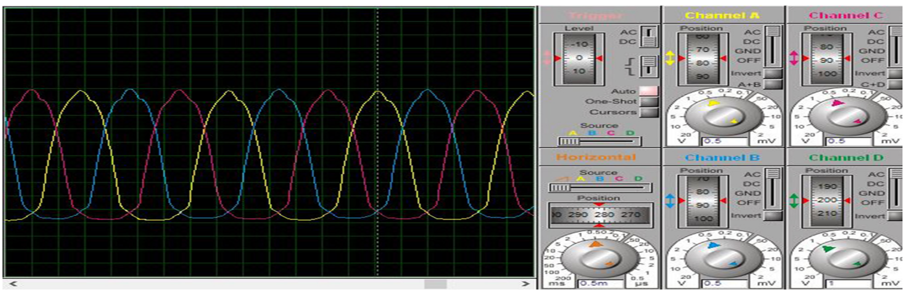

Fig. 15. Wave form when the motor rotate forward direction

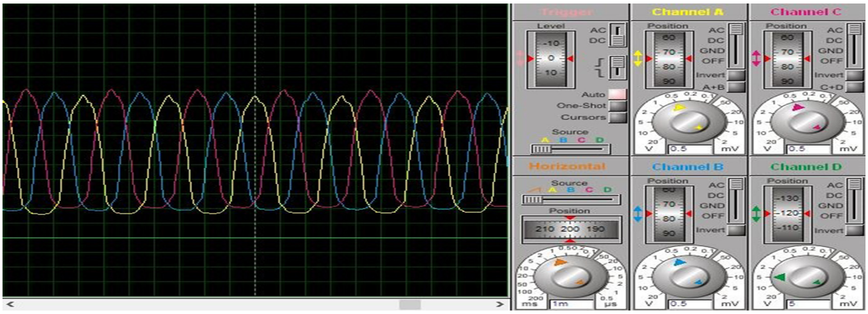

Fig. 16. Wave form when the motor rotate reverse direction

Comparison Simulation Results of SPWM and SVPWM: In the following figures show the wave forms of SPWM and SVPWM techniques using FFT analyzing by varying its modulation index. As per the Table 4, SVPWM gives 15% quality improvement of the fundamental output.

Table 4. Evaluations of SPWM and SVPWM at varying modulation index.

Technique	SPWM		SVPWM	
M. I. (M)	Output line voltage(peak)volt	THD (%)	Output line voltage (peak)volt	THD (%)
0.4	180.80	162.11	192.70	154.07
0.5	266.50	123.35	312.20	108.78
0.6	289.40	117.12	318.10	105.69
0.7	369.20	94.52	436.60	81.19
0.8	396.10	89.73	442.90	78.56
0.9	472.90	70.69	552.30	53.62
1.0	502.40	64.83	567.90	49.15

5 Conclusions

In this paper space vector pulse width modulation-based induction motor with proportional integral control model is designed through MATLAB software and also tested successfully by evaluating the parameters like stator current, rotor current, torque and speed. By keeping the ratio of stator voltage to frequency constant, this system tips can regulate the speed of the motor by controlling the frequency and voltage amplitude of the stator. SVPWM control system design and implementation is simple and trouble free. Besides electric vehicle application, these types of induction motors control system can be used in agricultural and industrial pumps. The modulation technique selected for the paper is space vector pulse width modulation with good exploitation of the DC link voltage and low current ripple. It is also relatively easy to implement in the hardware platform. These features also make it suitable for high-voltage high-power applications.

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