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# SVPWM Controlled Voltage Source Inverter Fed Induction Motor for an Electric Vehicle

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## Abstract:

Electric vehicle contains a significant role due to the rising prices of fossil fuel used in conventional vehicles and the increasing rate of carbon dioxide emission from conventional vehicles. Lithium-ion battery is engaged in the proposed work for supplying electricity to an AC three-phase induction motor through a three-phase voltage source inverter. The space vector pulse width modulation is a progressive modulation strategy for VSI connected an induction motor to control and to enhance the performance parameters likewise rotor speed and electromagnetic torque. Mainly, this paper deals with the two-level SVPWM scheme and the switching performance of the induction motor drive. The SVPWM controlled VSI fed induction motor is designed in MATLAB Simulink. This paper analyzes the Simulink model and its different parameters such as efficiency and total harmonic distortion of an AC three-phase induction motor.

*Keywords* — **Electric Vehicle (EV), Induction Motor (IM), Space Vector Pulse Width Modulation (SVPWM), Total Harmonic Distortion (THD), Voltage Source Inverter (VSI).**

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## I. INTRODUCTION

Conventional vehicles are allied with an internal combustion engine that take fossil fuel for driving the vehicles. Conventional vehicles are liable for enlargement of the carbon dioxide dissemination and the temperature on the earth as well. With the rising rate of usage of conventional vehicles, tariff of fossil fuel is also increased. Currently, an electric vehicle is perfect mode for the rising rate of fossil fuel. Electric vehicles are propelled through electricity from a battery pack to the electric motor engaged in it. Electric vehicles reduce the temperature on the earth and the $CO_2$ dissemination in the environment [1].

In the proposed work, a lithium-ion battery is employed for powering electric energy to an AC induction motor of an electric vehicle. Lithium-ion battery is broadly used rechargeable battery with a high energy transfer capability at a low self-discharge rate. Lithium-ion battery involves two electrodes – anode as a positive terminal electrode and cathode as a negative terminal electrode which are made from lithium carbon and metal oxide material respectively [2]. Both electrodes are immersed in the lithium salt used as an electrolyte for a lithium-ion battery. This lithium-ion battery can be charged either by connecting the battery charger plug into a power source or through the regenerative braking mode of the electric vehicle. During the charging process, lithium-particles transfer from negative terminal to positive terminal through a separator. When the lithium-ion battery supplying electric energy to an induction motor, lithium-particles move from positive terminal to negative terminal via a separator [2].

An electric vehicle contains voltage source inverter (VSI) for converting direct current from the li-ion battery into alternating current to an induction motor [3]. Generally, the pulse width modulation (PWM) produces high magnitude of harmonic distortion. Therefore, the space vector pulse width modulation

(SVPWM) scheme is proposed for an evaluation of the switching response of an inverter [4]. Squirrel cage type of induction motor is broadly used cause of the fix speed at variable frequency. Vector controlled induction motor obtains fast transient response from flux controlled current component and torque controlled current component [5]. The overall performance of the space vector scheme for an induction motor will be analysed in this paper.

## II. SPACE VECTOR CONTROL OF INDUCTION MOTOR

Space vector control strategy is termed as field-oriented control or variable frequency control method for an induction motor. Three-phase voltage source inverter linked induction motor is composed from the space vector pulse width modulation [3]. Space vector topology controls the stator current flowing through an induction motor. Space vector control is viable of producing full torque at zero speed and quick acceleration – deacceleration as well.

Schematic outline of the space vector control strategy of an induction motor [4] is appeared in the figure 1 as:

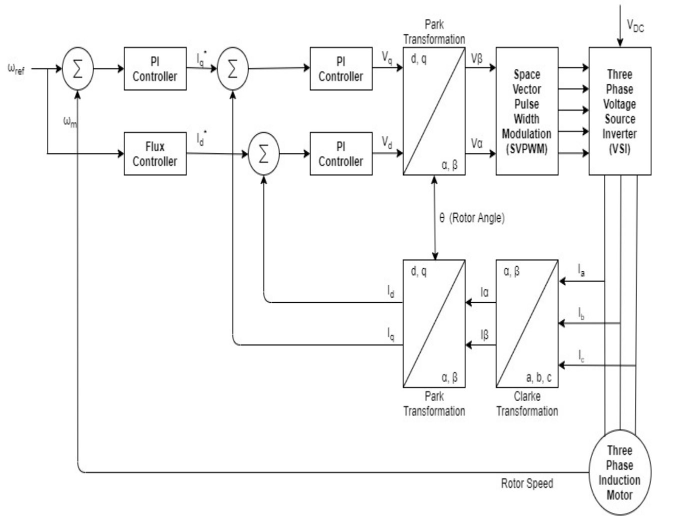



Fig. 1. Schematic outline of SVPWM Control of Induction Motor

Space vector control introduces to the dq – modelling of an induction motor. The dq – model deals with two axes – direct axis as a flux controlling component and quadrature axis as a torque controlling component. By using space vector control, the three-phase AC quantities are converted into two-phase quantities. Space vector control uses two type of transformations – Clarke transformation and Park transformation [5]. In Clarke transformation, three-phase quantities (a, b, c) are transformed into two-phase time variant quantities (α, β). In Park transformation, two-phase time variant quantities (α, β) are reformed into two-phase time invariant quantities (d, q).

The inputs for the SVPWM are the voltage vectors in a fixed reference frame and the outputs from the SVPWM are used to drive the inverter [4].

## III. SPACE VECTOR PULSE WIDTH MODULATION (SVPWM) SCHEME

The SVPWM signals are applied on a three-phase voltage source inverter. In an inverter, six metal oxide semiconductor field effect transistors (MOSFETs) are implemented for converting direct current into alternating current and to get a controlled output voltage [6]. In SVPWM scheme, the inverter takes controlled switching signals and produces less harmonic deviation.

The SVPWM scheme is considered with total eight state operations as shown in the figure 2 below. It shows two zero voltage states i.e $V_0$, $V_7$ etc. and six voltage vectors joined with the voltage source inverter. Among the six voltage vectors, three voltage vectors are the positive pole switches and the remaining three voltage vectors are the negative pole switches [7].

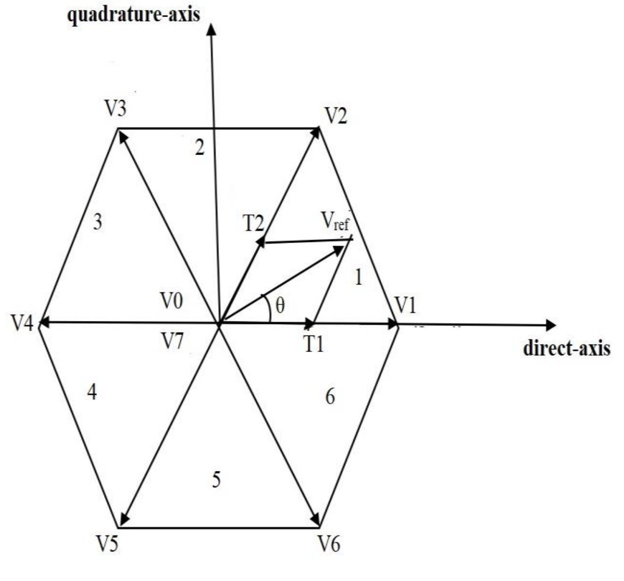



Fig. 2. Space Vector Diagram

The three phase supplied voltages from VSI to an IM are –

$$Va = Vm.sin(\omega t)$$
$$Vb = Vm.sin(\omega t - 120)$$
$$Vc = Vm.sin(\omega t - 240)$$

Where, $V_a$, $V_b$, and $V_c$ are the line voltage and $V_m$ is the terminal voltage's magnitude. Supplied frequency is referred as ω [8]. A relationship is established between αβγ and abc which can be given as:

$$V\alpha = \frac{2}{3}Va + \frac{1}{3}Vb - \frac{1}{3}Vc$$
$$V\beta = \frac{1}{\sqrt{3}}Vb - \frac{1}{\sqrt{3}}Vc$$
$$V\gamma = 0$$

Therefore, the direct and quadrature axes voltage can be given as:

$$\begin{bmatrix} Vd \\ Vq \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} V\alpha \\ V\beta \end{bmatrix}$$

Values of voltage at direct axis ($V_d$), voltage at quadrature axis ($V_q$), reference voltage ($V_{ref}$) and angle (θ) [9] can be given as:

$$\begin{bmatrix} Vd \\ Vq \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \end{bmatrix}$$
$$Vref = \sqrt{(Vd)^2 + (Vq)^2}$$
$$\theta = \tan^{-1}\frac{Vq}{Vd}$$

The SVPWM produces less magnitude of total harmonic distortion (THD). Total harmonic distortion can be characterized as a ratio of addition of all powers of the harmonic component to the fundamental component's power [7]. Through THD, the order of harmonic in the output current or voltage signal can be evaluated which means a distortion or deviation in sinusoidal waveform. THD is expressed in terms of percentage.

Total harmonic distortion in an output voltage is defined as a ratio of addition of all rms values of the harmonic components of output voltage to the fundamental aspect's rms value of output voltage [10]. Voltage THD is given as:

$$Voltage - THD = \frac{\sqrt{\sum_{h=2}^{h=\infty}(Voh - rms)^2}}{Vor - rms}$$

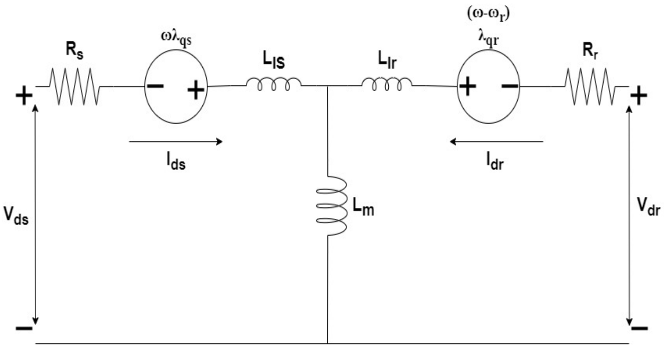
Total harmonic distortion in an output current is defined as a ratio of addition of all rms values of the harmonic components of output current to the fundamental aspect's rms value of output current [10]. Current THD is given as:

$$Current - THD = \frac{\sqrt{\sum_{h=2}^{h=\infty}(Ioh - rms)^2}}{Ior - rms}$$

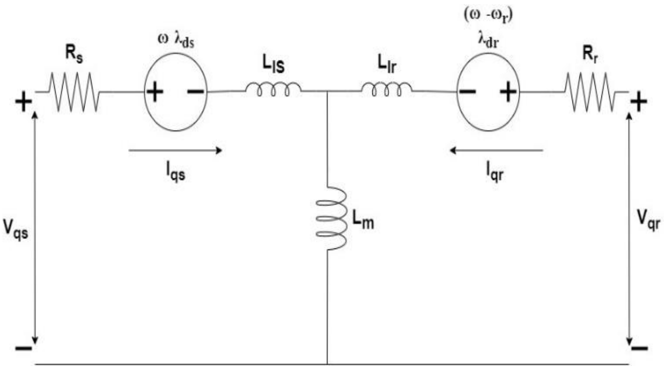
Current and voltage total harmonic distortion are expressed in terms of percentage.

## IV. MATHEMATICAL MODELING OF INDUCTION MOTOR

Mathematical layout of an AC three-phase induction motor is derived from dq-modeling as shown in the following figure 3 as:




(a) d-axis




(b) q-axis

Fig. 3. dq-Modeling of Induction Motor [4]

In mathematical modeling of an induction motor, three-phase AC quantities are altered into two axes – direct axis and quadrature axis. Direct axis component is the flux controlling current component ($I_{ds}$) whereas the quadrature axis component is the torque controlling current component ($I_{qs}$) of the induction motor [11].

The dynamic model of an AC induction motor rotates within two reference structures – stationary or fixed reference structure and rotating reference structure. Equations for voltage magnitude are also changing between the stator and rotor part of the IM. The voltage magnitude equation for an arbitrary reference frame can be determined through the appropriate value of speed to ω. The different values of speed are assigned as 0, $\omega_r$ and $\omega_e$ for the fixed reference structure, the rotor rotating reference structure and simultaneously rotating reference structure respectively [4].

Equations for voltage of the three-phase induction motor can be given as:

$$Vds = Rs(Ids) - \omega(\lambda qs) + \rho(\lambda ds)$$
$$Vqs = Rs(Iqs) + \omega(\lambda ds) + \rho(\lambda qs)$$
$$Vdr = Rr(Idr) - (\omega - \omega r)(\lambda qr) + \rho(\lambda dr)$$
$$Vqr = Rr(Iqr) + (\omega - \omega r)(\lambda dr) + \rho(\lambda qr)$$

Equations for flux linkage can be given as:

$$\lambda ds = (L1s).(Ids) + (Lm).(Ids + Idr)$$
$$\lambda qs = (L1s).(Iqs) + (Lm).(Iqs + Iqr)$$
$$\lambda dr = (L1s).(Idr) + (Lm).(Ids + Idr)$$
$$\lambda qr = (L1s).(Iqr) + (Lm).(Ids + Idr)$$

Where, the parameters are

$V_{ds}$ = voltage of stator circuit at direct axis
$V_{qs}$ = voltage of stator circuit at quadrature axis
$V_{dr}$ = voltage of rotor circuit at direct axis
$V_{qr}$ = voltage of rotor circuit at quadrature axis
$I_{ds}$ = current of stator circuit in direct axis
$I_{qs}$ = current of stator circuit in quadrature axis
$I_{dr}$ = current of rotor circuit in direct axis
$I_{qr}$ = current of rotor circuit in quadrature axis
$\lambda_{ds}$ = flux linkage for stator circuit in direct axis
$\lambda_{qs}$ = flux linkage for stator circuit in quadrature axis
$\lambda_{dr}$ = flux linkage for rotor circuit in direct axis
$\lambda_{qr}$ = flux linkage for rotor circuit in quadrature axis
$R_s$, $R_r$ = resistances of stator and rotor circuit
$L_{1s}$, $L_{1r}$ = inductances of stator and rotor circuit
$L_m$ = bilateral inductance between stator and rotor circuits
ω = angular velocity of rotation of stator magnetic field
$\omega_r$ = angular velocity of rotation of rotor
$(\omega-\omega_r)$ = angular velocity in proportionate of rotating reference structure
and ρ = d/dt.

Equations for voltages and flux linkages in term of inductance are converted in term of reactance due to more reliability and conveniency in putting the direct values of resistance and reactance [8]. The voltage equations can be given as:

$$Vds = Rs(Ids) - \frac{\omega}{\omega b}(\Psi qs) + \frac{\rho}{\omega b}(\Psi ds)$$
$$Vqs = Rs(Iqs) + \frac{\omega}{\omega b}(\Psi ds) + \frac{\rho}{\omega b}(\Psi qs)$$
$$Vdr = Rr(Idr) - \frac{(\omega - \omega r)}{\omega b}(\Psi qr) + \frac{\rho}{\omega b}(\Psi dr)$$
$$Vqr = Rr(Iqr) + \frac{(\omega - \omega r)}{\omega b}(\Psi dr) + \frac{\rho}{\omega b}(\Psi qr)$$

Equations for flux linkage are transformed into flux linkage per second which can be given as:

$$\Psi ds = (X1s)(Ids) + Xm[Ids + Idr]$$
$$\Psi qs = (X1s)(Iqs) + Xm[Iqs + Iqr]$$
$$\Psi dr = (X1r)(Idr) + Xm[Ids + Idr]$$
$$\Psi qr = (X1r)(Iqr) + Xm[Iqs + Iqr]$$

The current expressions are presented in terms of flux linkage which can be given as:

$$Ids = \frac{1}{X1s}(\Psi ds - \Psi dm)$$
$$Iqs = \frac{1}{X1s}(\Psi qs - \Psi qm)$$
$$Idr = \frac{1}{X1r}(\Psi dr - \Psi dm)$$
$$Iqr = \frac{1}{X1r}(\Psi qr - \Psi qm)$$

Where, the parameters of $\Psi_{dm}$ and $\Psi_{qm}$ are given as:

$$\Psi dm = Xm\left[\left(\frac{\Psi ds}{X1s}\right) + \left(\frac{\Psi dr}{X1r}\right)\right] = Lm[Ids + Idr]$$
$$\Psi qm = Xm\left[\left(\frac{\Psi qs}{X1s}\right) + \left(\frac{\Psi qr}{X1r}\right)\right] = Lm[Iqs + Iqr]$$

Using all the above equations, the expressions for electromagnetic torque, electrical and mechanical rotor speed [4] can be given respectively as:

$$Te = \left(\frac{3P}{4}\right)\left(\frac{1}{\omega b}\right)(\Psi ds\ Iqs - \Psi qs\ Ids)$$

$$\omega r = \int \left(\frac{1}{J}\right)(Te - Tl).dt$$

$$\omega r = \int \left(\frac{P}{2J}\right)(Te - Tl).dt$$

Where, P and $T_l$ are the number of poles and the load torque for the induction motor [4].

## V. SIMULINK MODEL & RESULT OF SVPWM FED INDUCTION MOTOR

A lithium-ion battery is engaged for supplying electric energy to an AC 3-phase induction motor through a 3-phase voltage source inverter with the space vector pulse width modulation scheme [9]. Simulink model and results are accomplished through MATLAB R2018a version. Lithium-ion battery specifications are given as:

TABLE I Lithium-ion Battery Specifications

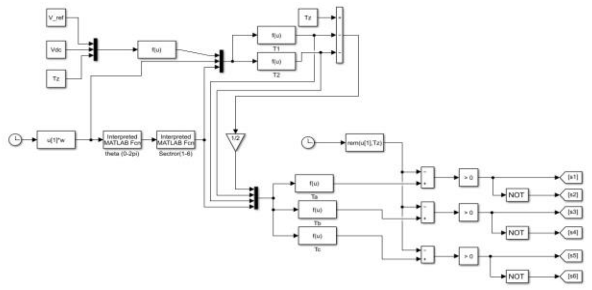
| **Type of Battery** | **Lithium-ion Battery** |
|---|---|
| Nominal Voltage | 400 V |
| Maximum Capacity | 250 Ah |
| Fully Charged Voltage | 465.60 V |
| Cut-off Voltage | 300 V |
| Internal Resistance | 0.016 Ω |

Parameters of an AC 3-phase induction motor are designated according to the SVPWM control of it [12]. The specifications are given as:

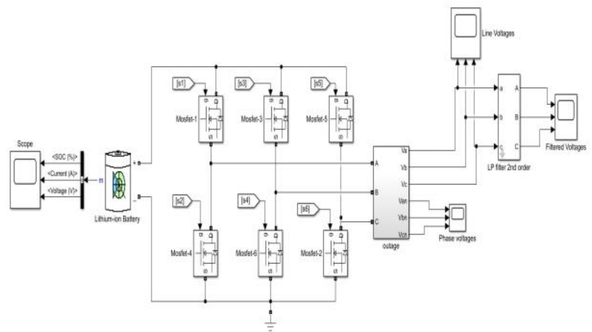
TABLE II Three Phase Induction Motor Specifications [13]

| **Type of Electric Motor** | **Three-Phase Squirrel Cage Type of Induction Motor** |
|---|---|
| Power | 50 HP (37 KW) |
| Voltage | 400 V |
| Frequency | 50 Hz |
| Rotor Speed | 1480 rpm |
| Resistance – $R_s$ | 0.01904 Ω |
| Resistance – $R_r$ | 0.01163 Ω |
| Inductances – $L_{1s}$ and $L_{1r}$ | 0.0526 Ω |
| Inductance – $L_m$ | 1.97 Ω |
| Moment of Inertia (J) | 0.37 Kg-m$^2$ |
| Load Torque | 240.56 N-m |
| Number of Poles | 2 |

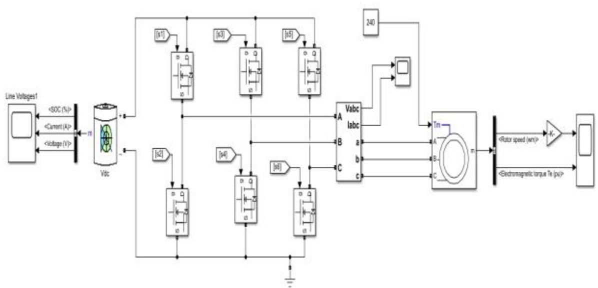
A Simulink model for the space vector pulse width modulation manipulate signals for a voltage source inverter with an induction motor is developed in MATLAB as demonstrated in figure 4 as:



(a) SVPWM Signals



(b) Voltage Source Inverter

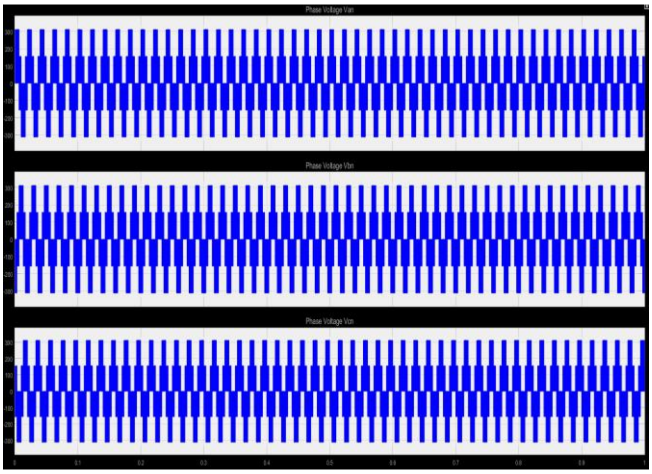


(c) Induction Motor

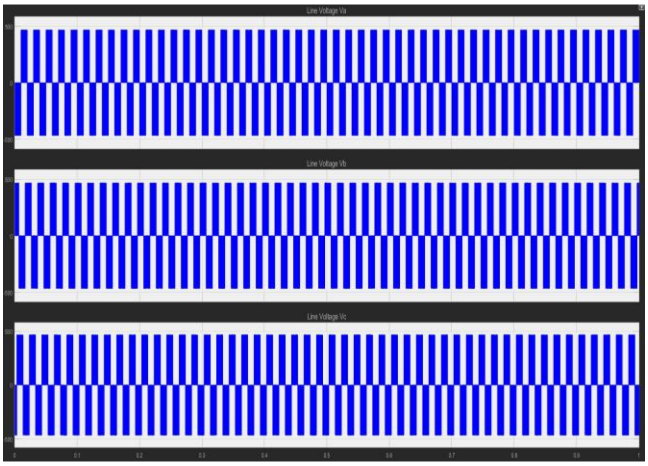
Fig. 4. SVPWM Controlled VSI Fed Induction Motor

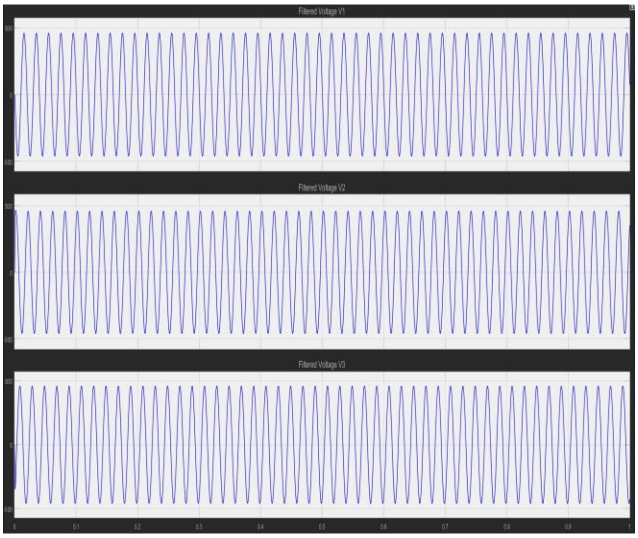
The Simulink results for the developed Simulink model of SVPWM controlled VSI [11] are shown in figure 5 as:



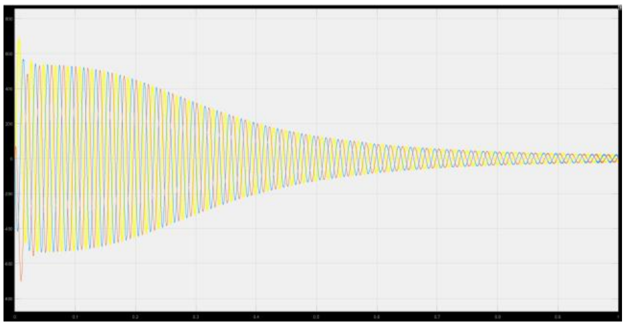
(a) Output Phase Voltage



(b) Output Line Voltage



(c) Output Filtered Voltage



(d) Output Current

Fig. 5 Simulink Results of SVPWM Controlled Three-Phase Voltage Source Inverter

Lithium-ion battery is engaged for transferring electric power to an induction motor. The outcome variables i.e. state-of-charge, current, voltage etc. are demonstrated for the proposed lithium-ion battery in the figure 6 as:

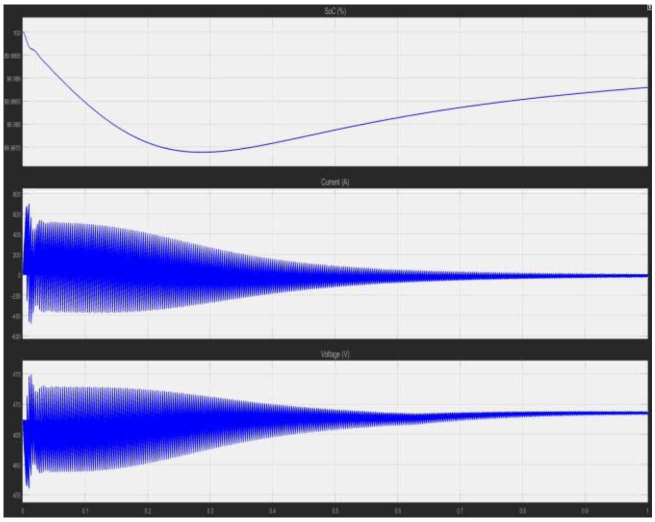


Fig. 6. Output Waveform of a Lithium-ion Battery

Outcome sketch for voltage-current from an induction motor of 50 HP, 400 V, 1480 RPM is displayed in the figure 7 as:

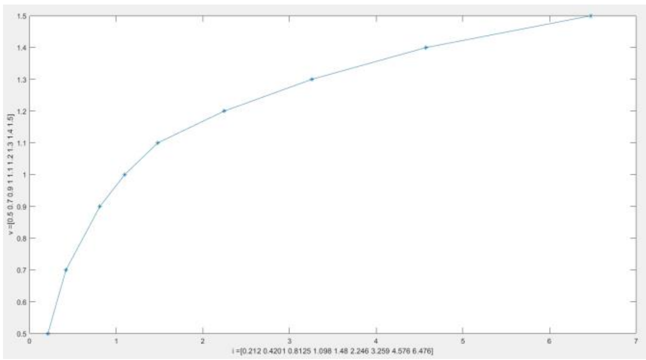
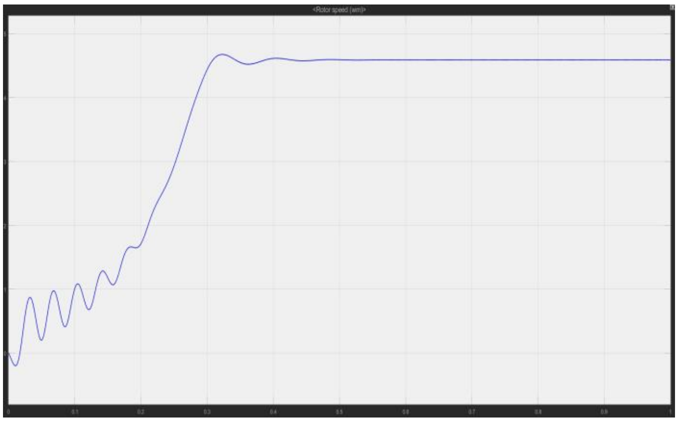


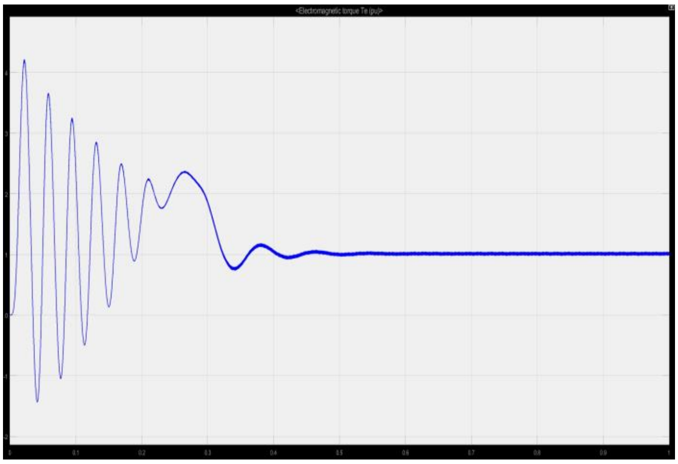
Fig. 7. Voltage-Current (VI) Result of Induction Motor

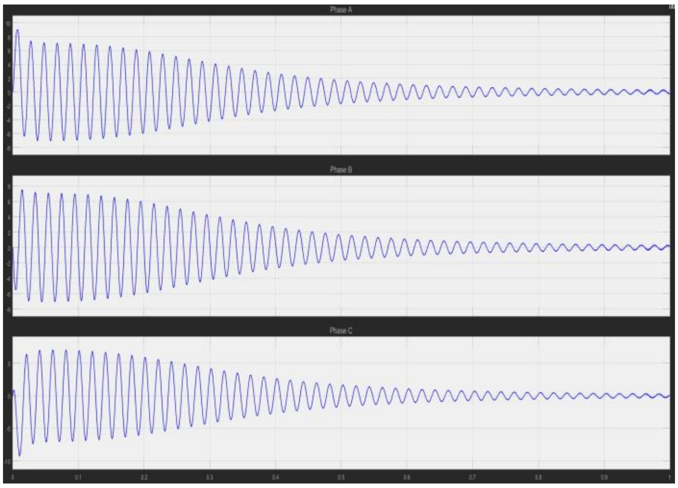
Figure 8 shows the different resulting parameters of an AC 3-phase induction motor such as rotor speed ($\omega_m$), electromagnetic torque ($T_e$) and stator current as [14]:



(a) Rotor Speed ($\omega_m$) Curve



(b) Electromagnetic Torque ($T_e$) Curve



(c) Stator Current

Fig. 8. Simulink Result of SVPWM Controlled VSI Fed Induction Motor

Through the simulated result of the SVPWM scheme for VSI fed Induction motor, total harmonic distortion (THD) reduces with a variation in carrier frequency [15]. Outcome of the total harmonic distortion (THD) is displayed in following figure 9 as:

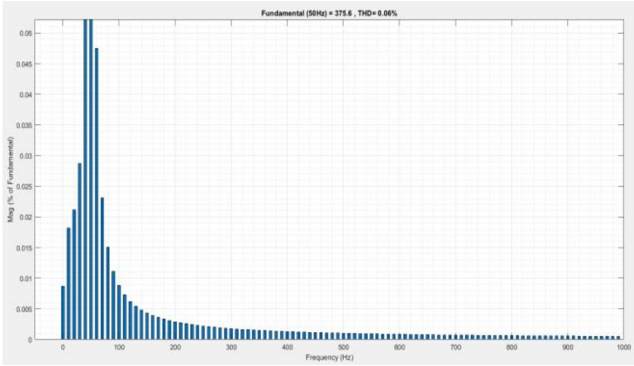


Fig. 9. Total Harmonic Distortion Outcome

## VI. CONCLUSION

In this research work, the space vector pulse width modulation control approach is carried out for a three-phase voltage source inverter fed induction motor. The paper extracts the simulated results of the output phase voltage, line voltage, filtered voltage and output current from the SVPWM controlled voltage source inverter.

This paper describes the Simulink modeling, performance and result of the proposed AC squirrel cage induction motor. The simulated results analyze the variation and the control in an induction motor's parameters likewise rotor speed, electromagnetic torque and stator current of an AC three-phase induction motor. In this paper, proposed induction motor's performance and reduction in total harmonic distortion are analyzed. By applying SVPWM signals through a 3-phase VSI, Total harmonic distortion for an AC induction motor is measured as low as 0.06%. However, the SVPWM scheme is complex but it is most important for controlling a voltage source inverter with an induction motor.

Proposed paper enhances new upcoming opportunities in the field of SVPWM for the researchers of all around the world. In future, SVPWM scheme will be used for current source inverter or impedance source inverter fed with the AC three-phase or five-phase induction motor.

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