RESEARCH ARTICLE OPEN ACCESS

Modelling and Simulation of Three Level VSI-Neutral Point Balancing -Fed AC Drive using Intelligence Techniques

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ABSTRACT
Multilevel inverter topology has developed recently as a very important alternative in the area of high power medium voltage energy control. In multilevel inverter, thethree basic types of topologies used are diode clamped inverter (neutral point clamped), capacitorclamped (flying capacitor) and cascaded multi cell with separate dc sources. Multilevel inverters are used in medium voltage and high power applications with less harmonic contents. This paper proposes a software implementation of neutral point clamped (NPC) three level voltage source inverter using space vector pulse width modulation (SVPWM) techniques. The inverter feeds an electrical system which is controlled by field oriented control (FOC).The improvement of the control technique is achieved using intelligence techniques. The operation of the electrical system is verified in steady state and transient state responses. This software implementation is performed by using matlab/Simulink software. This paper gives comparison between SVPWM three phase three level with neutral point clamped and without neutral point clamped. Finally, the comparative study of different techniques was implemented.
Keywords: Vector control, Neutral point clamped three level inverter, Space vector pulse width modulation, Induction motor, PI controller, Fuzzy logic controller and Hybrid controller.

I.Introduction:

Sinceits introduction in 1980, early interest in multilevel power conversion technology was triggered by the work of Nabae, etal,who introduced the neutral-point clamped (NPC) inverter topology. It was immediately recognized that this new converter had many advantages over the more conventionaltwo-level inverter. Later, in the early nineties the concept of the three-level converter was extended further and some new multilevel topologies were proposed [1]. Newly, improvements in power electronics and semiconductor technology have lead developments in power electronic systems.

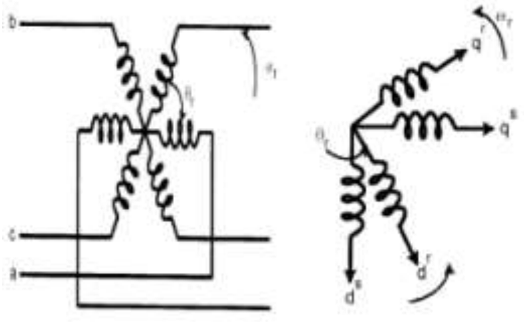
Multilevel inverters have gained much attention for the next generation medium voltage and high power applications. Three-level diode-clamped inverter also known as neutral point clamped (NPC).The three-level NPC inverter is used in this paper. Problems due to neutral-point voltage unbalance and narrow pulse width modulationits various balance control methods are discussed at length. The output voltage waveforms in multilevel inverters can be generated at low switching frequencies with high efficiency and low distortion. In recent years, nearby multilevel inverters various pulse width modulation (PWM) techniques have been also developed. Space vector PWM (SVPWM) technique is one of the most popular techniques gained interest recently. This technique results in higher magnitude of fundamental output voltage available as compared to sinusoidal PWM. But, SVPWMprocedure used in three-level inverters is more complex because of large number of inverter switching states. Multilevel inverters are that the voltage stress on each switching device is reduced. In addition, multilevel waveforms feature have less harmonic content compared to two level waveforms operating at the same switching frequency.

Nikola Tesla first developed the principles of multi-phase AC motors in 1882. Because an induction motor is less expensive to make, is electrically and mechanically robust, and it operates broad range of speed, torque and mechanical power, it is the most commonly used motor in industry [5,6]. Another attractive topic is the control scheme used to control an electric system. Field oriented control (FOC) is used to optimize the electric system. Intelligence techniques are used such as pi controller, fuzzy logic controller and hybrid controller in case of rotor speed and inverter current control.

This paper presents simplified method for the implementation of the Neutral point clamped inverter combined with a new space vector pulse width modulation technique using Matlab / Simulink. The operation of the electric system is performed in both cases considering the neutral point clamped (NPC) and not considering the neutral point clamped (NPC).

II. Dynamic d-q Model of Induction Motor:

The dynamic performance of an Ac machine is slightly complex because the three phase rotor windings move the respect to the three phase stator windings as shown in figure 1.



(a) (b)

Fig 1: (a) Coupling effect in three phase Stator and Rotor windings of motor,
(b) Equivalent two phase machine.

The Park's transformation is a three-phase to two-phase transformation for Asynchronous machine analysis [2]. It is used to transform the stator variables of a synchronous machine into a d-q reference frame that is fixed to the rotor.

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

For the two phase machine shown in figure 1(b) .we need to represent both d^s-q^s and d^r-q^r circuits and their variables in asynchronously rotating d^e-q^e frame.

Stator circuit equations,

$$V_{ds} = R_s i_{ds} + \frac{d\Psi_{ds}}{dt} - \omega_e \psi_{qs}$$

$$V_{qs} = R_s i_{qs} + \frac{d\Psi_{qs}}{dt} + \omega_e \psi_{ds}$$

Rotor circuit equations,

$$V_{qr} = R_r i_{qr} + \frac{d\Psi_{qr}}{dt} + (\omega_e - \omega_r)\psi_{dr}$$

$$V_{dr} = R_r i_{dr} + \frac{d\Psi_{dr}}{dt} - (\omega_e - \omega_r)\psi_{qr}$$

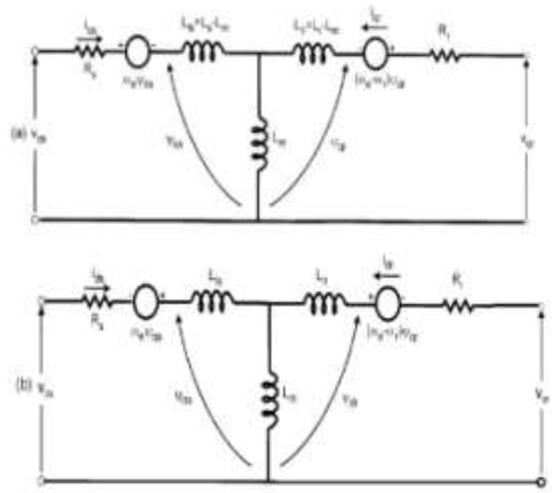


Fig 2: Dynamic d^e-q^e equivalent circuits of Machine (a) q^e -axis and (b) d^e – axis.

The flux linkage expressions in terms of the currents can be written as follows:

$$\Psi_{ds} = L_s i_{ds} + L_m i_{dr}$$
$$\Psi_{qs} = L_s i_{qs} + L_m i_{qr}$$
$$\Psi_{dr} = L_s i_{dr} + L_m i_{ds}$$
$$\Psi_{qr} = L_r i_{qr} + L_m i_{qs}$$

Therefore the voltage equations in the arbitrary reference frame are given by

$$\begin{bmatrix} v_{dsc} \\ v_{qsc} \\ v_{drc} \\ v_{qrc} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & -\omega_c L_s & L_m p & -\omega_c L_m \\ \omega_c L_s & R_s + L_s p & \omega_c L_m & L_m p \\ L_m p & -(\omega_c - \omega_r) L_m & R_r + L_r p & -(\omega_c - \omega_r) L_r \\ (\omega_c - \omega_r) L_m & L_m p & (\omega_c - \omega_r) L_r & R_r + L_r p \end{bmatrix}\begin{bmatrix} i_{dsc} \\ i_{qsc} \\ i_{drc} \\ i_{qrc} \end{bmatrix}$$

The development of torque by the interaction of air gap flux and rotor mmf; it will be expressed in general form, relating the d-q components of variables.

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\ (\Psi_{ds}\, i_{qs} - \Psi_{qs}\, i_{ds})$$

Where $L_s = L_{ls} + L_m$,
$L_r = L_{lr} + L_m$.

L_s& L_r = Self-inductance per phase of the stator and rotor windings.
R_s& R_r = Resistance per phase of the stator and rotor windings.
L_m = Mutual inductance of stator and rotor Windings.
W_m = Angular velocity of rotor
P = Number of poles
J = Load Inertia Constant respectively.

III.Field Oriented Control:

Vector control, also called **field-oriented control** (FOC), is a variable-frequency drive (VFD) control method where the stator currents of a three-phase AC electric motor are identified as two orthogonal components that can be visualized with a vector. One component defines the magnetic flux of the motor, the other defines the torque. The control system of the drive calculates from the flux and torque references given by the drive's speed control the corresponding current component references. Typically controllers are used to keep the measured current components at their reference values. Such complex stator motor current space vector can be defined in a (d,q) coordinate system with orthogonal components along d (direct) and q (quadrature) axes such that field flux linkage component of current is aligned along the d axis and torque component of current is aligned along the q axis [3,4]. So, in vector control, both flux & torque are control independently i.e., both are decoupled in nature. The vector control is also known as decoupling, orthogonal, or trans-vector control because of the separately excited dc motor like performance. The vector control is applicable to both induction and synchronous motor drives.

Vector control strategies are of two types.
1. Direct (or) Feedback vector control
2. Indirect (or) feed forward vector
Control

1. Direct vector Control:
The direct method of vector control attempts to directly measure or estimate the machine flux, and use this to determine the transformation angle.

2. Indirect vector control:
The control schemes generate inverter switching commands to achieve the desired electromagnetic torque at the shaft of motor. As shown in the Block diagram, Torque and Rotor Flux can be independently controlled by q-axis stator current and d-axis stator current respectively.

The q-axis Stator Current Reference i^*_{qs} is calculated from Command Torque Signal T^*_e as shown in below equation.

$$i_{qs}^* = \frac{2}{3} * \frac{2}{p} * \frac{Lr}{Lm} * \frac{T_e^*}{|\ \psi_r\ |\ \text{est}}$$

$|\ \psi_r\ |$ estis the Estimated Rotor Flux Linkage. It can be calculated by equation shown below.

$$|\ \psi_r\ |\ \text{est} = \frac{L_m\, i_{ds}}{1 + \tau_r\, s}$$

Where $\tau_r = \frac{L_r}{R_r}$is the rotor time constant.

The direct-axis stator current reference i^*_{ds} is obtained from reference rotor flux input $|\psi_r|^*$.

$$i_{ds}^* = \frac{\psi_r^*}{L_m}$$

The rotor flux position $\Theta_e$required for coordinates transformation is obtained from the rotor speed ω_r and slip frequency ω_{sl}. Θ_e is calculated as

$$\Theta_e = \int \omega_e dt = \int (\omega_r + \omega_{sl})\, dt$$

The slip frequency ω_{sl} is calculated from the stator reference current i^*_{qs} and the motor parameters.
ω_{sl} is given by

$$\omega_{sl} = \frac{L_m\, R_r}{\psi_r\, L_r} i_{qs}$$

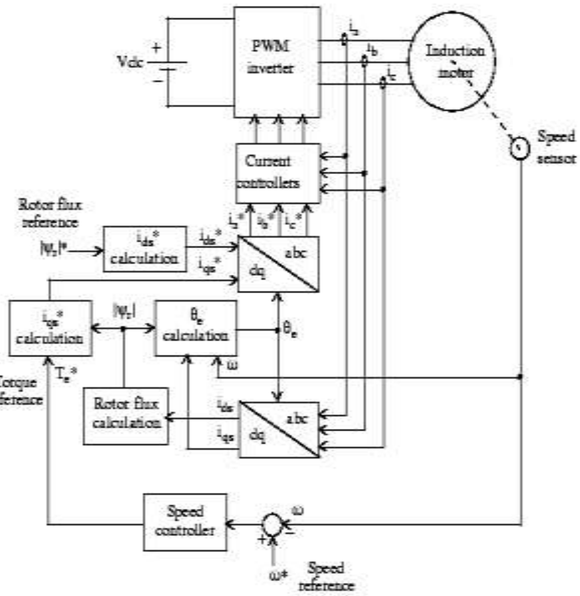


Fig 3: Block Diagram of Indirect Vector Control Technique.

To provide a good dynamic response during transient conditions, the speed controller should maintain the motor speed equal to reference speed input [8].

IV. Three Level Inverter:

The circuit consists of 12 power switching devices and 6 clamping diodes. Each arm contains four IGBTs, four anti parallel diodes and two neutral clamping diodes. And the dc bus voltage is split into three levels by two series connected bulk capacitors C1, C2 two capacitors have been used to divide the DC link voltage into three voltage levels, thus the name of 3-level.The middle point of the two capacitors can be defined as the neutral point . The diode-clamped inverter was also called the neutral-point clamped (NPC) inverter [7].

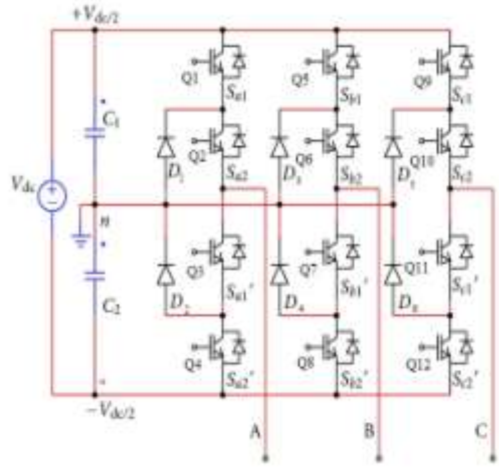


Fig 4: Diode Clamped Three Level Inverter.

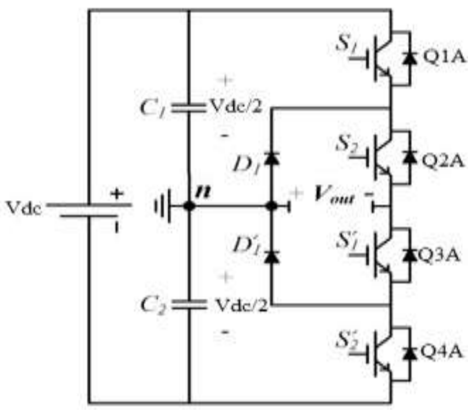


Fig 5:Phase A of Three Level Inverter.

Table 1: Switching Configuration.

Switches on	Switches off	Output Voltage
Q_{1A}, Q_{2A}	Q_{3A}, Q_{4A}	$+V_{DC}$
Q_{2A}, Q_{3A}	Q_{1A}, Q_{4A}	0
Q_{3A}, Q_{4A}	Q_{1A}, Q_{2A}	$-V_{DC}$

4.1. Space Vector Pulse Width Modulation:

Space vector pulse width modulation (SVM) is moderately different fromthe PWM methods. With PWMs, the inverter can be thought of as three separate push-pull driver stages which create each phase waveform independently. SVM however treats the inverter as a single unit. Specifically the inverter can be driven to eight unique states [9].Which include six active and two zero states. These vectors form a hexagon which can be seen as consisting of six sectors spanning 60° each. The reference vector which represents three-phase sinusoidal voltage is generated using SVPWM by switching between two nearest active vectors and zero vectors. Modulation is capable by switching the state of inverter [10]. SVM is a digital modulation technique where the objective is to generate PWM load line voltages. This is done in each sampling period by properly selecting the switching states of inverter and calculation of the suitable time period for each state.

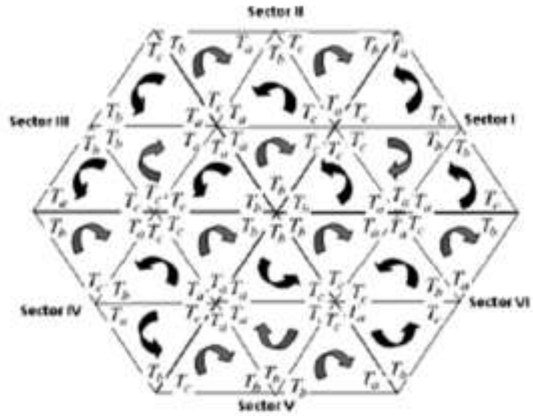


Fig6: Switching Sequence for Three-level SVPWM Inverter.

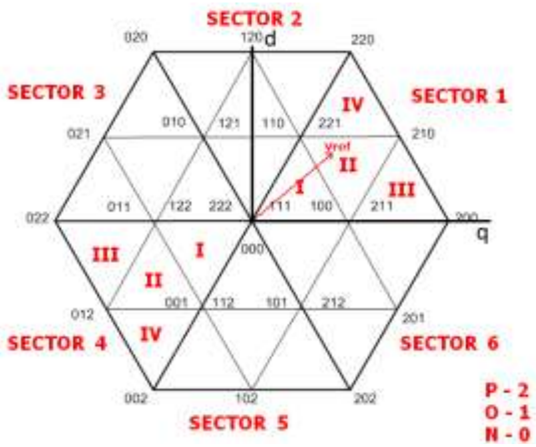


Fig 7: Sectors and their Regions for Three-level Inverter.

The space vector diagram that is shown in Figure 6 can be used to calculate the time for each sector (I to VI). Each sector has four regions (1 to 4), as shown in Figure 7, with the switching states of all vectors. By using the same strategy that was used in chapter two, the sum of the voltage multiplied by the interval of chose space vector equals the product of the reference voltage Vref and sampling period TS [13,15].To illustrate, when reference voltage is located in region 2 of sector I then the nearest vectors to reference voltage are V5, V17, and V7 [12] and the next equations explain the relationship between times and voltages:

$$V_5T_a+V_{17}T_b+V_7T_c=V_{ref}T_s$$

$$T_a+T_b+Tc = T_s$$

Where T_a,$T_b$and $T_c$are the times for V_5, V_{17} and V_7 respectively.

The Equation for total time is

$$T_a = T_s [1-2m_a \sin\Theta]$$

$$T_b = T_s \left[2m_a \sin\left(\frac{\pi}{3}+\theta\right) - 1\right]$$

$$T_C = T_s \left[1 - 2m_a \sin\left(\frac{\pi}{3}+\theta\right)\right]$$

V. Speed Controller:

5.1 PI Controller:

The Combination of proportional and integral terms is important to increase the speed of the response and also to elimate the steady state error.

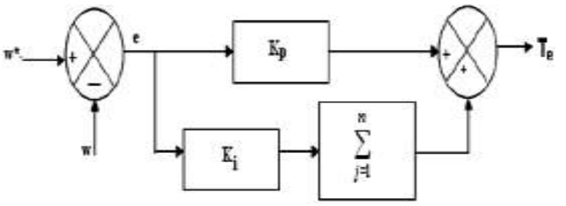


Fig 8: Block Diagram of PI Controller.

Command Torque is the output signal of controller where Kp is the proportional gain and Ki is the integral gain.

$$T_e = Kp_e + Ki \int_e dt$$

5.2. Fuzzy Logic Controller:

In drive operation, the speed can be controlled indirectly by controlling the torque which, for the normal operatingregion, is directly proportional to the voltage to frequency. The speed is controlled by fuzzy logic controller whose output is the reference current of the inner dc current controller. Fuzzy Logic control (FLC) has proven effective for complex, non-linear and imprecisely defined processes for which standard model based control techniques are impractical or impossible. Fuzzy Logic, unlike Boolean or crisp logic, deals with problems that have vagueness, uncertainty and use membership functions with values varying between 0 and 1.In fuzzy logic a particular object has a degree of membership in a given set, which is in the range of 0 to 1. The essence of fuzzy control algorithms is a conditional statement between a fuzzy input variable A and fuzzy output variable B. In general a fuzzy variable is expressed through a fuzzy set, which in turn is defined by a membership function. The torque is controlled by varying the dc current. The complete block diagram of the fuzzy logic controller is shown in figure 9.

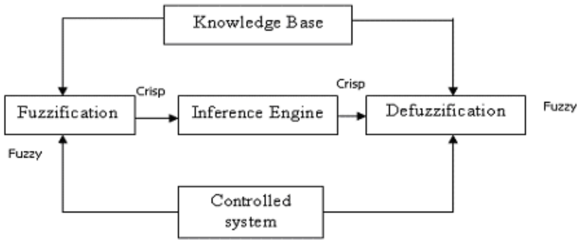


Fig 9 : Internal Structure of the Fuzzy Logic Controller

The fuzzy controller is considered as follows:

1. Seven fuzzy sets are used for e (n) and**δ**e (n).
2. Nine fuzzy sets are used for V (n).
3. Fuzzification using continuous universe of Discourse.
4. Defuzzification using the ‘‘centroid’’ method.
5. Mamdani’s minimum fuzzy implication.
6. Triangular membership functions

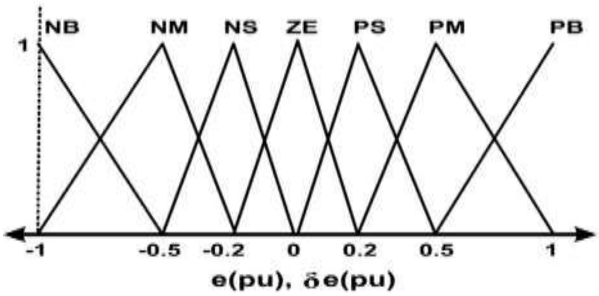


Fig 10: Input Membership Functions for error speed (e) & rate of change of error speed (**δ**e).

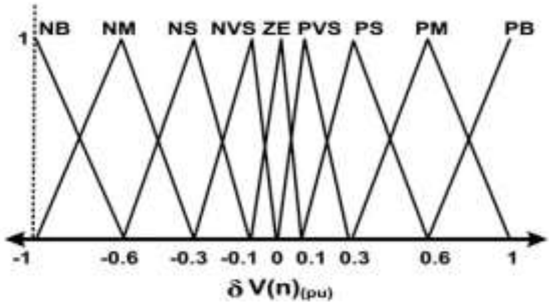


Fig 11: Output Membership Functions for Fuzzy Logic Controller.

Table 2: Rule Base for Fuzzy Logic Controller

δe \ e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NVS	ZE
NM	NB	NB	NM	NS	NVS	ZE	PVS
NS	NB	NM	NS	NVS	ZE	PVS	PS
ZE	NM	NS	NVS	ZE	PVS	PS	PM
PS	NS	NVS	ZE	PVS	PS	PM	PB
PM	NVS	ZE	PVS	PS	PM	PB	PB
PB	ZE	PVS	PS	PM	PB	PB	PB

Triangular Membership functions are used to represent input variables such as NB (negative big), NM (negative medium),NS (negative small), ZE (zero), PS (positive small), PM (positive medium), PB (positive big) and output variables such as NB (negative big), NM (negative medium),NS (negative small), NVS (negative very small), ZE (zero), PVS (positive very small),PS (positive small), PM (positive medium), PB (positive big) Here, Membership functions should be normalized between -1 to +1.The Fuzzy Rules are represented using IF-THEN form [11,14]. MAX-MIN Inference algorithm and Center of Gravity Defuzzification Approach is used to get Crisp output from Fuzzy Logic Controller. The fuzzyrules were designed based on the dynamic behaviour of the error signal.

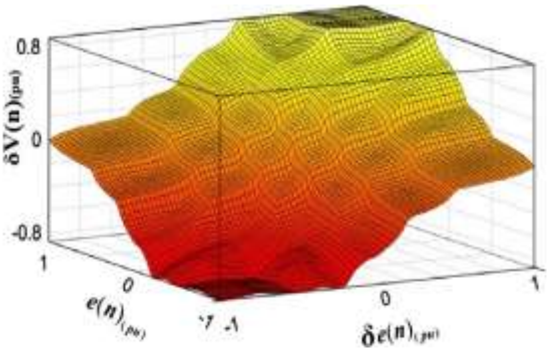


Fig 12: Fuzzy Logic Controller Surface.

The Fuzzy Logic Controller Surface is the output plotted against the two inputs. It is an interpolation of the effect of the 49 rules of Table 2.

5.3. Hybrid Controller:

The hybrid controller comprises PI-controller and Fuzzy Controller connected in parallel.This controller has the advantages of both PI and Fuzzy Logic controller. Fuzzy logic is used for pre-compensation of reference speed, which changes reference speed given to PI controller in accordance to rotor speed.

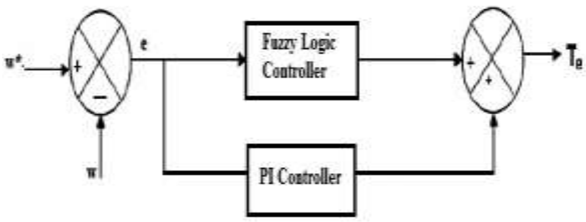


Fig 13: Block diagram of Hybrid Controller.

VI. Simulation Model:

The Block Diagram of proposed System consists of Field oriented Control, Space Vector Pulse Width Modulation and Induction Motor as shown in the below figure.

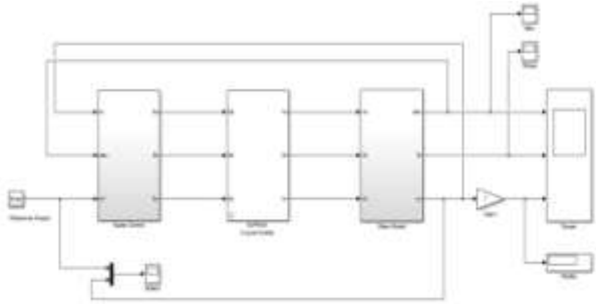


Fig 14: Simulink Model for Block Diagram of Proposed System.

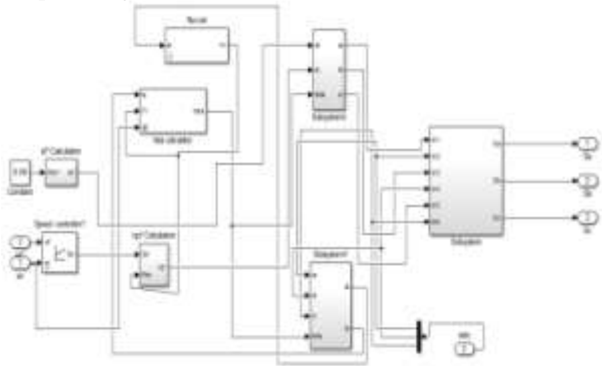


Fig 15: Simulink Model for Vector Control - PIController.

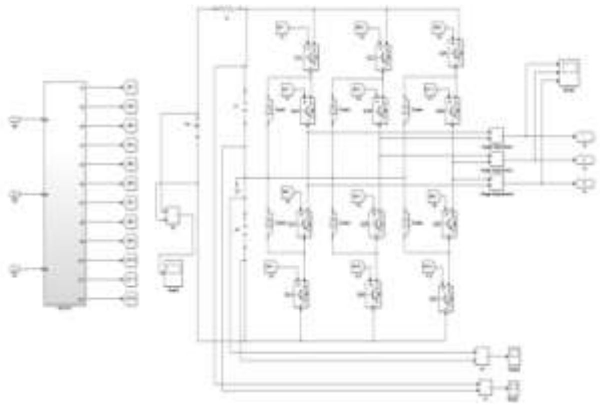


Fig 16: Simulink Model For With Neutral Point Clamped-SVPWM.

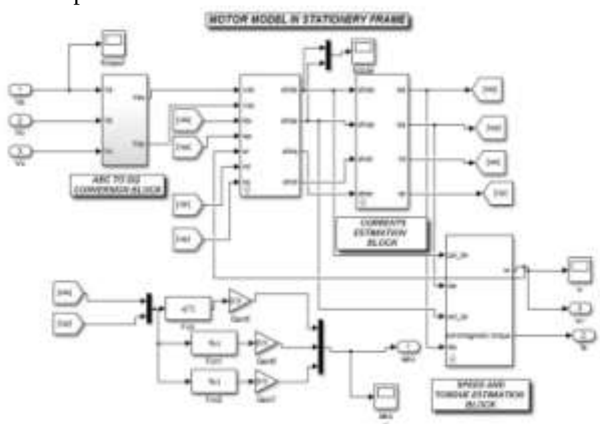


Fig 17: Simulink Model for Induction Motor.

VII. Simulation Results:

In this section, the simulation of the ‘‘electric system, three-level inverter’’ system is studied. The control scheme appliedin the system is the one presented.The inverter used is a three-level voltage source inverter and theswitching pattern is generated via the above SVPWM. The NP possible is studied in detail in case of considering and not considering the NP clamped. The system is considered in steady state and transient responses. The parameters used in this simulation are shown in Table 3 and Table 4.

The system is simulated for a period of t = 3s. During this period, the speed response (change of reference speed), thetorque response (change of reference torque) and steady state of the induction motor are considered. The switching frequency is set to F_s = 5 kHz and the dc bus voltage is V_{dc}= 460 V. The following subsections validate the system behaviour in speed and torque response. The steady state operation is also shown.

Table 3: Parameters used in Inverter.

Parameters	Nominal Values
Power Electronic Device	IGBT/Diode
Snubber Resistance(R_s)	1000 Ω
Snubber Capacitance(C_s)	∞
Internal Resistance(R_{on})	0.001 Ω
Forward Voltage of the IGBT (V_f)	0.8V
Forward Voltage of the Diode (V_f)	0.8V
Capacitance of the capacitors (C_1 and C_2)	1.5mF

Table 4: Parameters used in Induction motor.

Parameters	Nominal Values
Nominal Power(P)	50HP
Voltage(V)	460V
Frequency(F)	$50H_z$
Stator Resistance(R_s)	0.087 Ω
Rotor Resistance(R_r)	0.228 Ω
Mutual Inductance(L_m)	0.165mH
Stator Inductance(L_s)	0.17mH
Rotor Inductance(L_r)	0.17mH
Moment of Inertia(J)	0.089

7.1. Without Neutral point Balancing:

The induction motor is considered to have pass the starting period and operates with reference speed W_r= 120rad/s and reference torque T_L = 100 Nm. At time t = 3 s the reference speed changes from W_r= 120rad/s to W_r= 150 rad/s, while the reference torque from TL=100Nm and T_L=150Nm.In the below figures, the system behaviour is Shown during the speed response and Torque response without Neutral PointClamped.

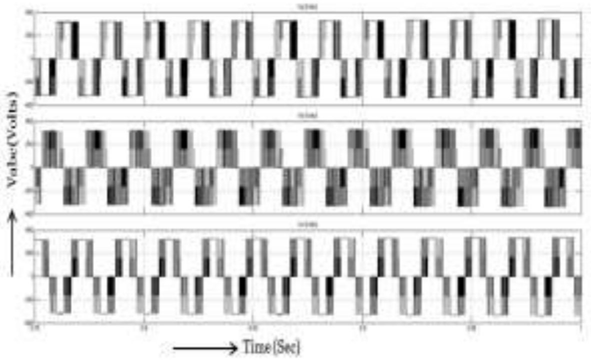


Fig 18: Phase Voltage (V_{abc}) of the Inverter without Neutral Point Clamped.

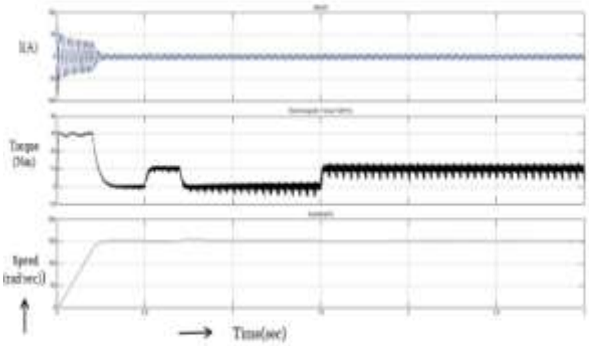


Fig 19:Current (I_{abc}), Torque and Speed using PI Controller.

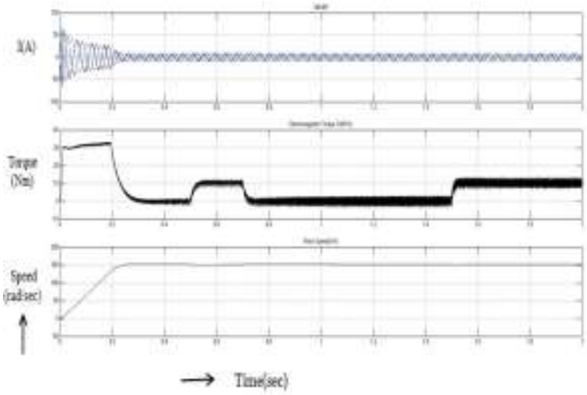


Fig 20: Current (I_{abc}), Torque and Speed using Fuzzy Logic Controller.

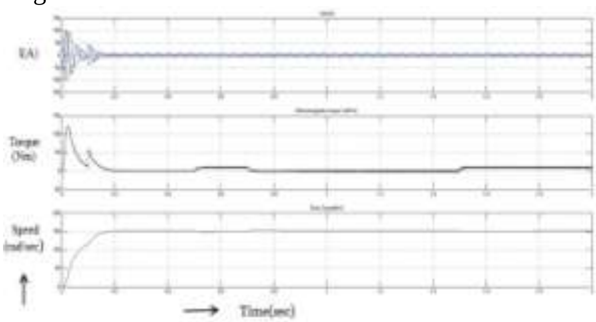


Fig 21: Current (I_{abc}), Torque and Speed using Hybrid Controller.

7.2. With Neutral point Balancing:

The induction motor is considered to have pass the starting period and operates with reference speed W_r= 120rad/s and reference torque T_L = 100 Nm. At time t = 3 s the reference speed changes from W_r= 120rad/s to W_r= 150 rad/s, while the reference torque from TL=100Nm and T_L=150Nm.In the below figures, the system behaviour isshown during the speed response and Torque response with Neutral PointClamped.

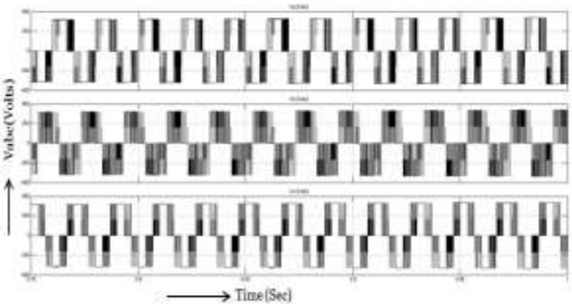


Fig 22: Phase Voltage (V_{abc}) of the Inverter without Neutral Point Clamped.

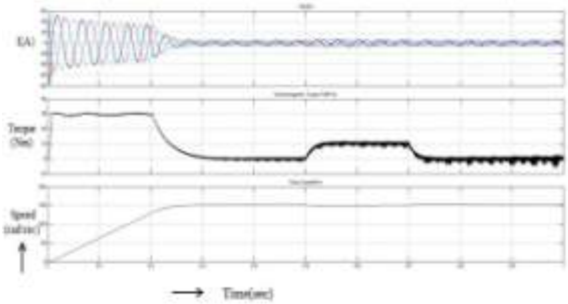


Fig 23: Current (I_{abc}), Torque and Speed using PI Controller.

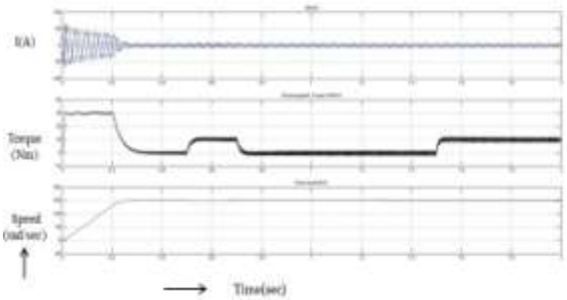


Fig 24: Current (I_{abc}), Torque and Speed using Fuzzy Logic Controller.

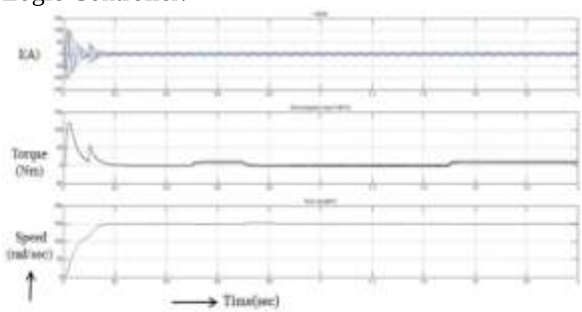


Fig 25: Current (I_{abc}), Torque and Speed using Hybrid Controller.

7.3. Performance Comparison:

Table 5:Specificationswithout Neutral point Balancing.

Parameters / Controllers	Torque Ripple(Nm)	Armature Current(Amp)
PI Controller	11	17
Fuzzy Logic Controller	6	10.5
Hybrid Controller	3.5	8

Table 6: Specificationswith Neutral point Balancing.

Parameters / Controllers	Torque Ripple (Nm)	Armature Current(Amp)
PI Controller	7.5	12.7
Fuzzy Logic Controller	4.2	9.2
HybridController	3	7

VIII. Conclusion:

A complete implementation and analysis is done regardingthe application of the SVPWM control scheme on the three-level voltage source inverter and induction motor presented using Matlab/Simulink. In order to achieve improved transient responses ofthe induction motor, pi controller, fuzzy logic controllers and hybrid controller were used. The NP balancingpromisingof the three-level inverter was examined in steady state and transient responses of the induction motor, while considering and not considering the NP balancing, combined with the proposed SVPWM. The capacitors voltage ripples during speed and torque response were limited using the NPC. In steady state, capacitors voltages were balanced with very small voltageripples using the NPC technique. The high quality output signals of the inverter have proved the good system operation using the NPC. The advantageof the proposed SVPWM combined with the NP balancing techniquewas established.Finally,the Hybrid controller preformsrespectable compared with Conventional PI controller and Fuzzy logic controller.

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