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Direct Torque Control of Induction Motor using3 Level and 5 Level PWM Inverter

Utpal Mahitcha[1], Prof Shimi S. L.[2], Dr. S. Chatterji[3]

[1]M.E. Student, Electrical Engineering Dept., NITTTR, Chandigarh, utpalrm@yahoo.com
[2]Assistant Professor, Electrical Engineering Dept., NITTTR, Chandigarh, shimi.reji@gmail.com
[3]Professor and Head, Electrical Engineering Dept., NITTTR, Chandigarh, chatterjis@yahoo.com

Abstract- Multi-level inverter technology is being used in multitude of high-voltage, high-power energy systems which include high-power drive applications for electric vehicles,mills, conveyors, pumps, fans, blowers, compressors, etc. Multilevel inverters offer considerable inherent advantages as compared to their two-level counter parts.Multi-level inverter circuit is obtained by connecting number of smaller discrete voltage sources so they generate the output voltage waveforms with more steps of smaller magnitudes, which is more closer to sine wave. The problems associated with two level inverters are electromagnetic interference, switching losses, switch voltage stress, and harmonic distortion.
Field Orientation Control and Direct Torque Control are two well-known, high performance methods for speed control of induction motors Out of these two methods motor control by direct torque control has become more popular.It gives high dynamic performance of instantaneous electromagnetic torque. The major attributes of DTC method are ability to achieve fast response of torque and flux, simple control scheme, less computational requirements and offers decoupled control of torque and flux. Work presented in this paper deals with simulation of Direct Torque Control of Induction Motor Drive using Three Level and Five Level PWM Inverter using Diode Clamped Multilevel Inverter topology, simulations of are carried out in MATLAB/SIMULINK

Keywords—Multilevel inverter, diode clamped multilevel inverter, direct torque control(DTC),space vector pulse width modulation (SVPWM), torque ripple, flux ripple.

I. INTRODUCTION

The ratings of power apparatus for various industrial applications are on increase. The power demand for motor drives and other industrial utilities are in the range of medium voltage and megawatt power level. The direct connection of a single power semiconductor switch to a medium becomes a difficult task. In order to mitigate this situation a multilevel power converter structure have been developed as an alternative in high power and medium voltage situations [2-3]. The multilevel converter circuits are being used since more than two and half decades. Since then many various topologies of multilevel invertershave been developed.

II. MULTILEVEL INVERTERS

Multilevel inverter consists of series of power semiconductor switches along with several dc voltages sources at lower level; with this power conversion is achieved and a stair case voltage waveform is obtained. The multiple dc voltage sources may consist of capacitors, batteries, and voltage sources from renewable energy. The commutation of the power switches add up these multiple dc voltage sources which reach a very high value at the output; however, the rated voltage of the power semiconductor switches depends only upon the rating of the dc voltage sources to which they are connected i.e. power semiconductor switches have to withstand rated voltage. Fig.1 shows the schematic of one phase leg of multilevel inverters with different number of levels; here the action of power semiconductors can be approximated with an ideal switch with several switch positions. A two level inverter generates an output voltage with two values (levels) with respect to the negative terminal of the capacitor as seen in Fig.1, while the three level inverter generates three voltages, and so on.

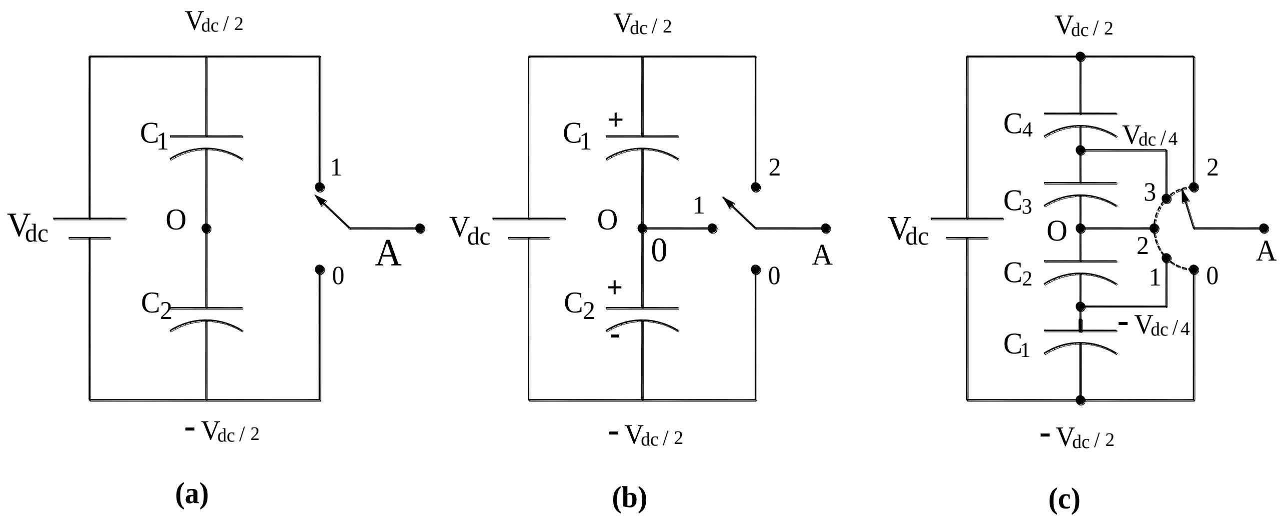


Fig. 1 One Phase Leg of (a) Two Level Inverter (b) Three Level Inverter (c) Five Level Inverter

Considering that m is the number of steps of the phase voltage with respect to negative terminal of the inverter[4], then the number of steps in the voltage between two phase of the load and k is

$$k = 2m + 1 \qquad (1)$$

And the number of steps p in the phase voltage of a three phase load in star connection can be given as

$$p = 2k - 1 \qquad (2)$$

The inverter circuits generating three or more levels of voltage are termed as multilevel inverter. This was introduced by Nabaeet. al. [1]. With increase in the number of levels in the inverter, the output voltage will have more steps and hence staircase voltage waveform would be generated. With more number of steps in output, the waveform will be closer to a sine wave and hence it will have reduced harmonic distortion. But as the number of level increases the complexity in control and voltage imbalance problems are introduced. The advantages of multilevel inverters can be summarized as bellow

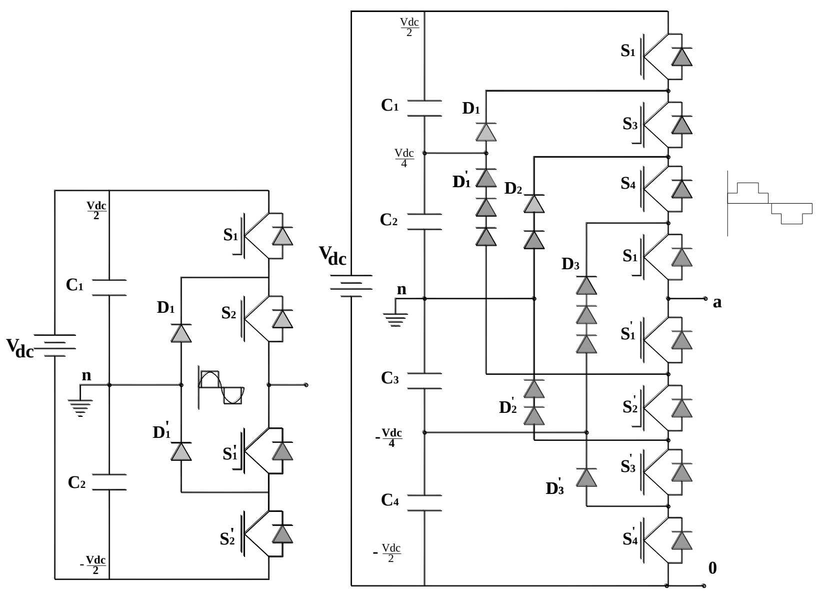
- Good power quality due to greater availability of voltage levels.
- Good electromagnetic compatibility (EMC).
- Output voltage generated has extremely low dv/dt and lower distortion.
- Lower switching losses, as switching frequencies of the devices can be reduced,
- Filters with smaller reactive components,
- Ratings of the components used reduce.

Various topologies of multi-level inverters are reported in the literature [1]-[5]. The most common multi-level inverter topologies are as follows :

- Diode Clamped/Neutral-Point-Clamped (NPC),
- Flying Capacitors (Capacitor Clamped),
- Cascaded H-Bridge and
- Dual Inverter Fed Open Ended Winding IM Structure.

III DIODE CLAMPED MULTILEVEL INVERTERS

The diode-clamped multilevel inverter circuit consists of clamping diodes and cascaded dc capacitors which generate ac voltage waveforms with multiple levels. The diode clamped inverter circuits with three, four and five level topology are popular. Diode clamped inverter was first used for three level inverter circuit, it was known as neutral point clamped (NPC) inverter as the mid voltage level was defined as neutral point [1].



(a) (b)

Fig. 2 Diode Clamped Multilevel Inverter Topologies (a) Three Level (b) Five Level Inverter

A three-level diode-clamped inverter is shown in Fig. 2(a). In this circuit, two series-connected bulk capacitors, C_1 and C_2 split the dc-bus voltage into three levels. The middle point of the two capacitors, n can be defined as the neutral point. The output voltage has three states: $V_{dc}/2$, 0, and $-V_{dc}/2$. When switches $S_1$and S_2 are turned on, voltage level $V_{dc}/2$ is obtained, when switches S_1' and S_2' are turned on voltage level obtained is $- V_{dc}/2$, and for the 0 level, S_2 and S_1' should be turned on.

Presence of diodes D_1 and D_1' in this circuit makes it different from conventional two level inverters. The function of diodes D_1 and D_1' is to clamp the switch voltage to half the level of the dc-bus voltage. When both $S_1$and S_2 turn on, the voltage across a and 0 is V_{dc}, i.e. $V_{ao}=V_{dc}$. In this case, D_1' balances out the voltage sharing between S_1' and S_2' with S_1' blocking the voltage across C_1 and S_2' blocking the voltage across C_2. It can be noticed that output voltage V_{an} is ac, and $V_{ao}$is dc. The difference between V_{an} and V_{ao} is the voltage across C_2, which is $V_{dc}/2$. If the output is removed out between a and o, then the circuit becomes a dc/dc converter, which has three output voltage levels V_{dc}, $V_{dc}/2$ and 0.

Fig. 2(b) shows a five-level diode-clamped multilevel inverter circuit in which the dc bus consists of four capacitors C_1, C_2, C_3 and C_4. For dc bus voltage V_{dc}voltage across each capacitor is $V_{dc}/4$, and device voltage stress will be limited to one capacitor voltage level $V_{dc}/4$, through clamping diodes. Thus for 'm' level inverter the switching device has to block voltage of $V_{dc}/(m-1)$

In order to understand how the staircase voltage is synthesized, considering the neutral point n as output phase voltage. There are five switch combinations that synthesize five level voltages across a and n.

1) For voltage level $V_{an}=V_{dc}/2$, turn on all upper switches S_1-S_4.
2) For voltage level $V_{an}=V_{dc}/4$, turn on three upper switches S_2-S_4 and one lower switch S_1'.

3) For voltage level V_{an}=0, turn on two upper switches S_3-S_4 and two lowerswitch S_1'-S_2'
4) For voltage level V_{an}=-V_{dc}/4 , turn on one upper switch S_4 and three lower switches S_1'-S_3'.
5) For voltage level V_{an}=-V_{dc}/2 , turn on all lower switches S_1'-S_4'.

There are four complimentary switch pairs in each phase. Switch pairs (S_1, S_1'), (S_2, S_2'), (S_3, S_3') and (S_4, S_4') are complementary switch pairs. The complementary switch pair is defined such that turning on one of the switches will exclude the other from being turned on.

Although each active switching device is only required to block a voltage level of V_{dc}/(n-1) , the clamping diodes must have different voltage ratings for reverse voltage blocking. Using of D_1' of Fig. 2(b) as an example, when lower devicesS_2'- S_4' are turned on, D_1' needs to block three capacitor voltages, or $3V_{dc}$/4.

Similarly, D_2 and D_2' need to block $2V_{dc}$/4, and D_3 needs to block $3V_{dc}$/4. Assuming that each blocking diode voltage rating is the same as the active device voltage rating, the number of diodes required for each phase will be (m-1) x (m-2). This represents quadratic increase in m. When m is sufficiently high, the number of diodes required will make the system impractical to implement. If the inverter runs under PWM, the diode reverse recovery of these clamping diodes becomes the major design challenge in high-voltage high power applications.

IV. DIRECT TORQUE CONTROL

High dynamic performance control of the electromagnetic torque of an induction motor can be achieved mainly by means of two control strategies: Field Oriented Control (FOC) and Direct Torque Control (DTC). Field oriented control was developed in early seventies by F. Blaschke [6]. FOC is a field regulation method of ac motor by changing coupled system to decoupled system. By this method, the excitation current and load current can be controlled separately. Hence, flux and torque also can be separately controlled similar in DC motor. The FOC method required current controller, coordinate transformation and current regulator to control pulse-width-modulation in the inverter system; this increases the complexity of the system [9].

Relatively, new control technique known as Direct Torque Control (DTC) was proposed by I.Takahashi [7] which controls electromagnetic torque and flux in an induction motor. DTC method works on the basis of the errors between the reference and the estimated values of torque and flux; with this method it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits. The direct torque control method gives fast torque response and high efficiency at every instant [6]. It is possible to get quick torque response in transient operation and harmonic losses and acoustic noise are also reduced. However DTC has some disadvantages like difficulty to control torque and flux at very low speed; high current and torque ripple; variable switching frequency behavior etc.

Fig. 3 shows the block diagram of Direct Torque Control drive for a Voltage source Inverter fed induction motor. It is seen that there are two different loops related to the magnitudes of the stator flux modulus and torque. The reference values for stator flux modulus and the torque are compared with the estimated values, the resulting error values are fed into a two level and a three level hysteresis block respectively.

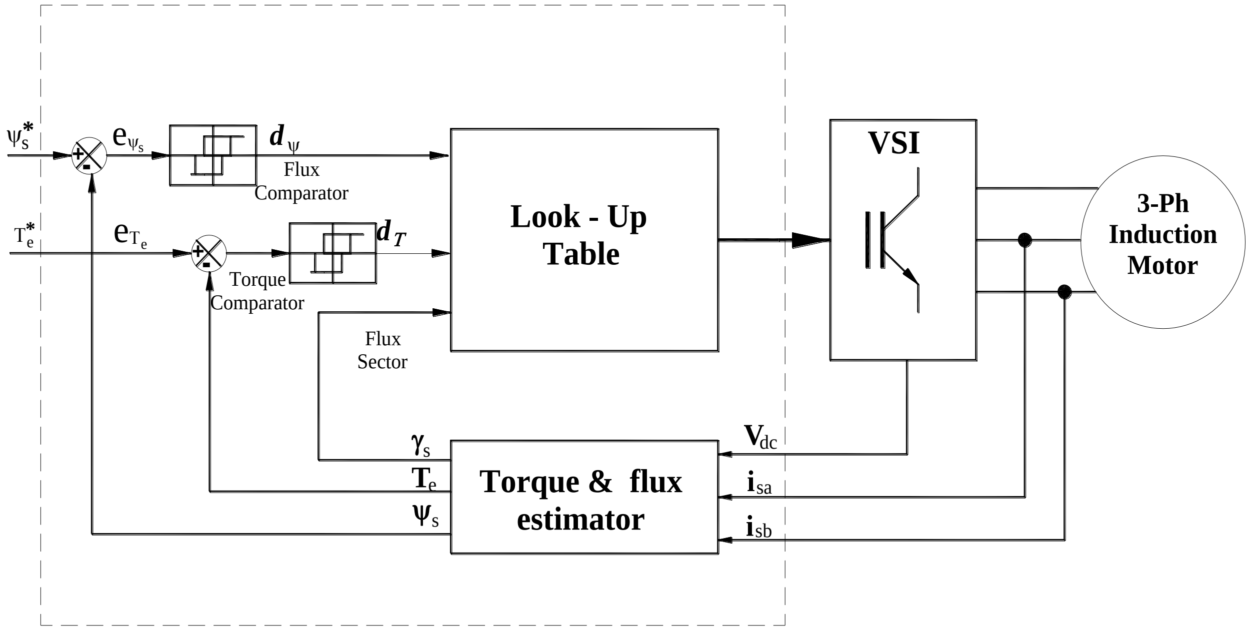


Fig. 3 Block Diagram of Direct Torque Control

The outputs of the stator flux error and torque error hysteresis block together with the opposition of the stator flux are used as input to the Look Table (Table.1).

The torque and flux are controlled simultaneously by choosing appropriate and then applying suitable voltage vectors which limit these quantities within their hysteresis bands

"Table 1.Switching States In DTC"

Kγ(Sector No)		**1**	**2**	**3**	**4**	**5**	**6**
Dψ (Flux Error)	**dT (Torque Error)**						
$D\psi = 1$	dT=1	V_2	V_3	V_4	V_5	V_6	V_1
	dT=0	V_7	V_0	V_7	V_0	V_7	V_0
	dT=-1	V_6	V_1	V_2	V_3	V_4	V_5
$D\psi = -1$	dT=1	V_3	V_4	V_5	V_6	V_1	V_2
	dT=0	V_0	V_7	V_0	V_7	V_0	V_7
	dT=-1	V_5	V_6	V_1	V_2	V_3	V_4

Principle of DTC can be elaborated using induction motor model. The expression for torque in an induction motor with P number of poles is given as :

$$T_e = \frac{3}{2} P \frac{L_m}{L_s L_r - L_m^2} |\overline{\Psi}_r||\overline{\Psi}_s| \sin(\theta_{rs}) \qquad 3$$

It can be noticed that torque is dependent on the stator flux (ψ_s), rotor flux (ψ_r) and angle between their vectors (θ_{rs}). Considering d-q axis format, the voltage across the stator coil as expressed in d and q axis :

$$\overline{V}_{ds} = R_s \overline{i}_{ds} + L_s \frac{d\overline{i}_{ds}}{dt} \quad 4$$

$$\overline{V}_{qs} = R_s \overline{i}_{qs} + L_s \frac{d\overline{i}_{qs}}{dt} \quad 5$$

The term $L_s \frac{d\overline{i}_{ds}}{dt}$ represents the change in stator flux in d and q axis respectively the above equations can be reformulated as

$$\overline{V}_{ds} = R_s \overline{i}_{ds} + L_s \frac{d\overline{\psi}_{ds}}{dt} \quad 6$$

$$\overline{V}_{qs} = R_s \overline{i}_{qs} + L_s \frac{d\overline{\psi}_{qs}}{dt} \quad 7$$

Solving above equations for $\overline{\psi}_{ds}$ and $\overline{\psi}_{qs}$ yields following formulas.

$$\overline{\Psi}_{ds} = \int(\overline{V}_{ds} - R_s \overline{i}_{ds})dt \quad 8$$

$$\overline{\Psi}_{qs} = \int(\overline{V}_{qs} - R_s \overline{i}_{qs})dt \quad 9$$

$$\overline{\Psi}_{s} = \overline{\Psi}_{s} + j\,\overline{\Psi}_{qs} \quad 10$$

This means that stator flux can be estimated as long as stator current is observable. Once d-q stator currents are known, the stator flux vector and the electromagnetic torque can be obtained by 10 and 11

$$T_e = \frac{3}{2} P(i_{qs}\psi_{ds} - i_{ds}\psi_{qs}) \quad 11$$

Based on the formulas mentioned above, a Simulink models for flux and torque estimators have been designed as shown in Fig.4

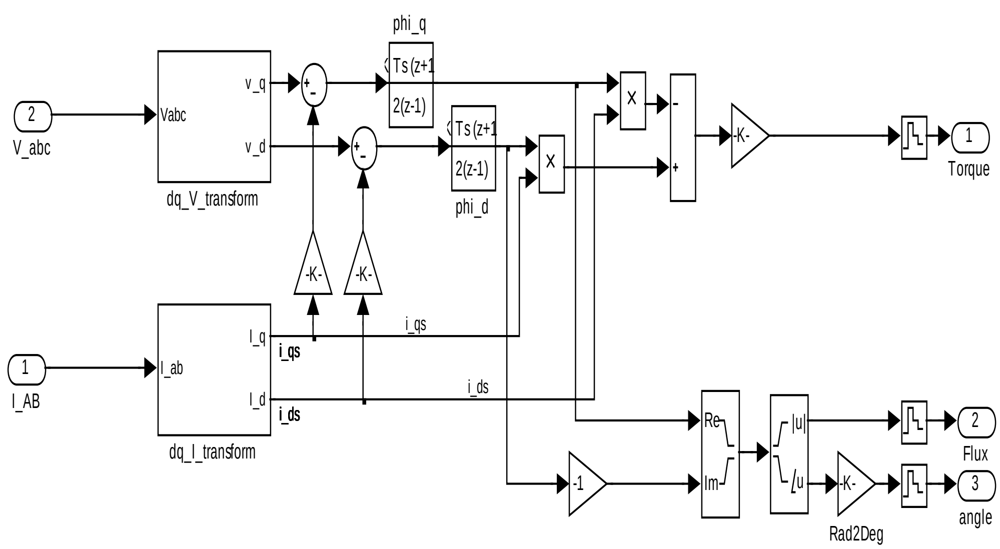


Fig. 4: Simulink Diagram of Torque & Flux Estimator Block

The estimated stator flux and torque are to be separately controlled. The stator flux $(\Delta\vec{\psi}_s)$ varies due to the applied stator voltage vector $(\Delta\vec{V}_s)$ during interval of time (Δt). i.e.

$$\Delta\vec{\psi}_s = \Delta\vec{V}_s\Delta t \qquad 12$$

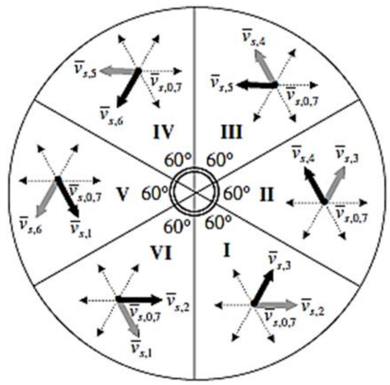


Fig. 5: Six Equal Sectors with Different Set of Voltage Vector

Therefore the stator flux is controllable if a proper selection of the voltage vector is made. As seen in Fig.5 Stator flux plane is divided into six sectors where each one has a set of voltage vectors. Bold arrow indicates the decreasing of the stator flux while the light arrow indicates the increment.

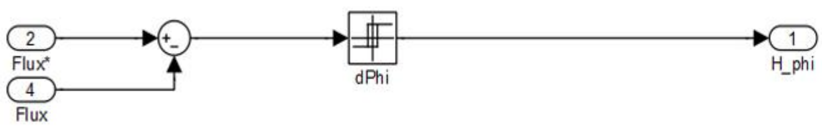


Fig. 6 : Simulink Diagram of Flux Hysterisis Controller

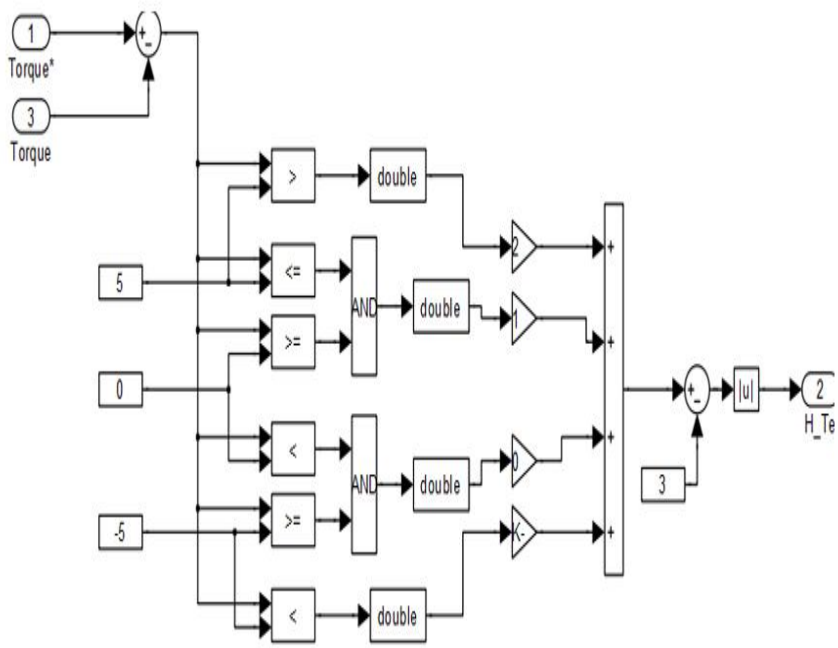


Fig. 7 Simulink Diagram of Torque Hysterisis Controller

The estimated stator flux is decreased or increased in order to match the manner of the desired or reference stator flux. However, a hysteresis band should be allowed and hence a 2 level hysteresis comparator is used for accurate design. The flux controller is shown in Fig. 6. The flux error which is due to the difference between the estimated and desired stator flux is fed to the hysteresis comparator which in turn produces the flux error status

The instantaneous electromagnetic torque is a sinusoidal function of the angle between stator and rotor fluxes abbreviated by (ψ_s) and (ψ_r) respectively.

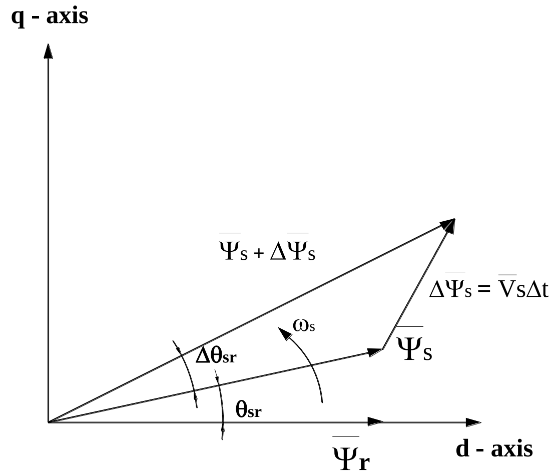


Fig. 8 : Space Vectors of Stator and Rotor Fluxes

The relation between these two flux vectors can be illustrated as in Fig. 8. Where the angle between them is denoted by θ_{sr}.

It can be observed that when the stator flux changes quickly θ_{sr} will be greatly varied causing a high variation in the output torque. Therefore , inverter voltage vectors must be poroperly selected in order to obtain a faster speed response and hence good dynamic performance can be obtained.

V. SPACE VECTOR PULSE WIDTH MODULATION (SVPWM)

The Space Vector Pulse Width Modulation (SVPWM) method is an advanced, computation intensive PWM techniques for inverter fed induction motor drives [16]. It has superior performance. It has following merits. It directly uses the control variable given by the control system and identifies each switching vector as a point in complex (α, β) space. It is suitable for digital signal processor (DSP) implementation. It can optimize switching sequences. In the SVPWM scheme, the sampled value of the reference voltage space vector which is the combined effect of the three-phase voltages is realized by switching the nearest voltage space vectors among the inverter voltage vectors. The SVPWM implementation involves the sector identification, switching-time calculation, switching-vector determination, and optimum-switching-sequence selection for the inverter voltage vectors [3]. The sector identification can be done by coordinate transformation [10] or by repeated comparison of the three phase reference voltages. The lookup tables can be used for determining the switching vectors in optimum switching sequence. The calculation of the duration of the switching vectors can be simplified using the mapping technique, in which the identified sector of the multilevel inverter is mapped to a corresponding sector of the two-level inverter [13-15]

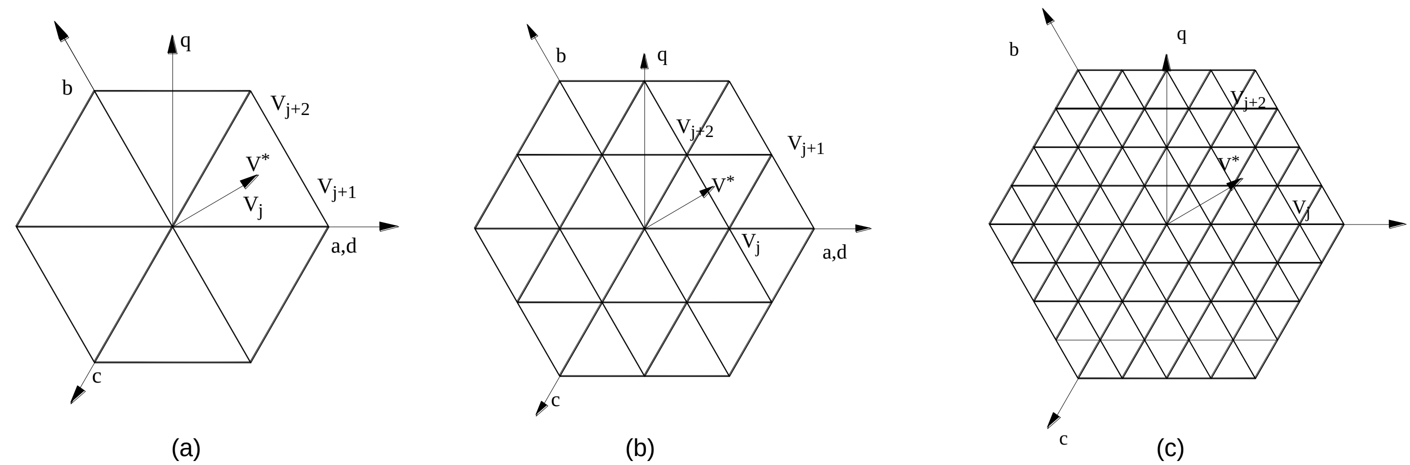


Fig. 9 Space Vector Diagram (a) Two Level Inverter (b) Three Level Inverter (c) Five Level Inverter

The space vector diagram of any three-phase n-level inverter consists of six sectors. Each sector consists of $(n-1)^2$ triangles. The tip of the reference vector can be located within any triangle. Each vertex of any triangle represents a switching vector. A switching vector represents one or more switching states depending on its location. There are n^3 switching states in the space vector diagram of an n-level inverter. The SVPWM is performed by suitably selecting and executing the switching states of the triangle for the respective on-times. It is also known It is also known as "Nearest Three Vector" (NTV) approach. The performance of the inverter significantly depends on the selection of these switching states.

The SVM technique can be easily extended to all multilevel inverters [4].Fig.9 shows space vectors for the traditional two, three, and five-level inverters. These vector diagrams are universal regardless of the type of multilevel inverter.

The adjacent three vectors can synthesize a desired voltage vector by computing the duty cycle (T_j , T_{j+1} , and T_{j+2}) for each vector.Each sector of outer hexagon of three level SVM can be divided into four smaller triangles, indexed as shown in Fig. 9 Each of these smaller triangles is then considered as on sectorof two level hexagon, with the similar redundancy on the origin.

$$V^* = \left(\frac{T_j V_{j+} T_j V_j + T_{j+2} V_{j+2}}{T} \right) \quad 13$$

As seen in the space vector diagram of a five level inverter. There are six sectors (S_1-S_6), sixteen triangles in a sector, and complete 125(n^3, n=5) switching conditions in this space vector diagram.

As the number of levels increases, redundant switching states and the complexity of selecting switching states increase dramatically. But for higher level inverters the actual sector containing the tip of the reference space vector need not be identified, but the center of a sub-hexagon containing the reference space vector is identified and using the center of the sub-hexagon, the reference space vector is mapped to the innermost sub-hexagon, and the switching sequence corresponding to a two-level inverter can be determined. Thus two-level vectors are translated to the switching vectors of the multilevel inverter by adding the center of the sub-hexagon to the two-level vectors. This can be extended to any n-level inverter [15].

VI SIMULATION AND RESULTS

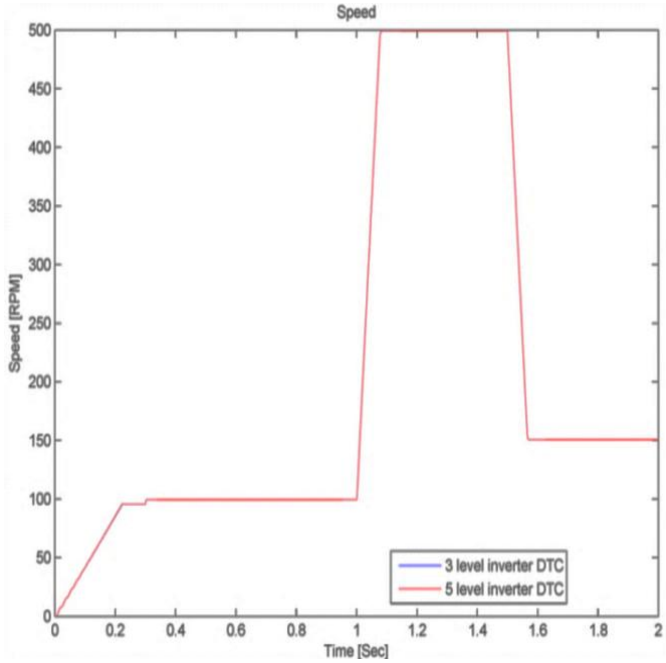


Figure 10: Comparison in speed of Induction Motor for 3-Level and 5-level PWM Inverter

As seen in the Fig.10 above, combined speed response of induction motor with Three Level PWM inverter and Five Level PWM inverter for a step change in speed is shown. The set point is 100 RPM, 500 RPM and 150 RPM on t = 0, 1 and 1.5 Sec Respectively. The response is almost SAME.

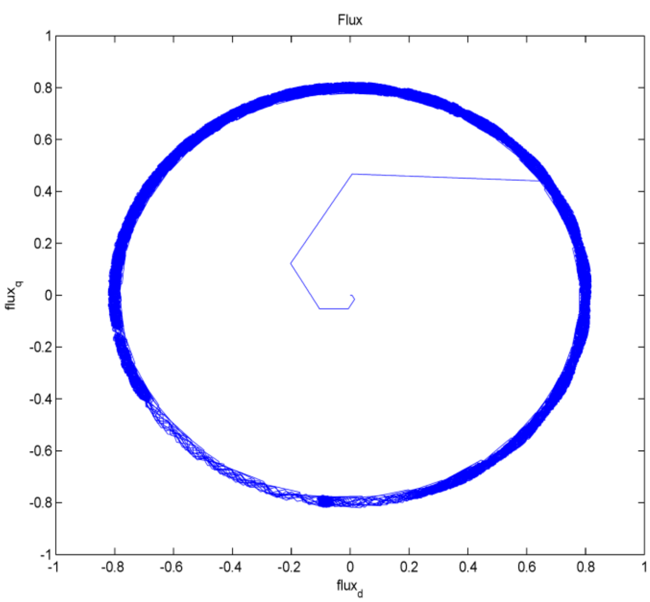


Fig.11: Flux Trajectory of DTC Drive withThree-LevelInverter

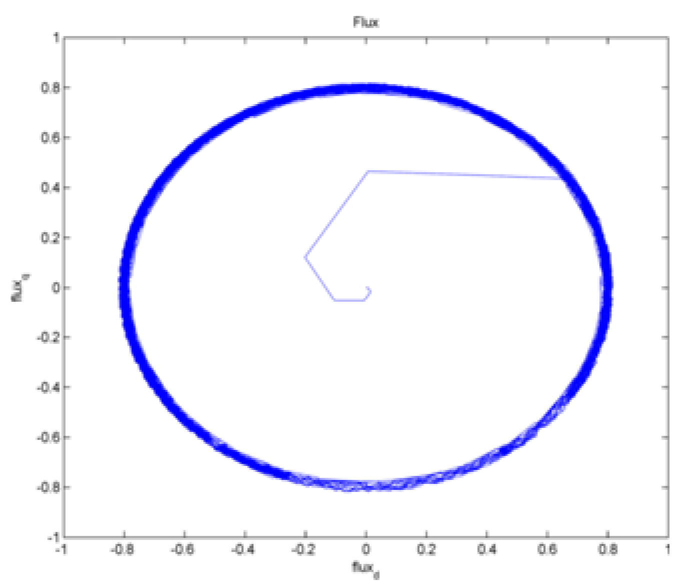


Fig.12: Flux Trajectory of DTC Drive with Five-LevelInverter

The Fig.11 shows the stator flux trajectory for DTC drive with Three-Level Inverter, the flux trajectory is smooth indicates that the DTC drive has reduced ripples in flux and speed response.

The Fig. 12 above shows the flux response of DTC drive with Five-Level Inverter. The response flux trajectory is almost similar with that of Three level inverter as shown in Fig.11.

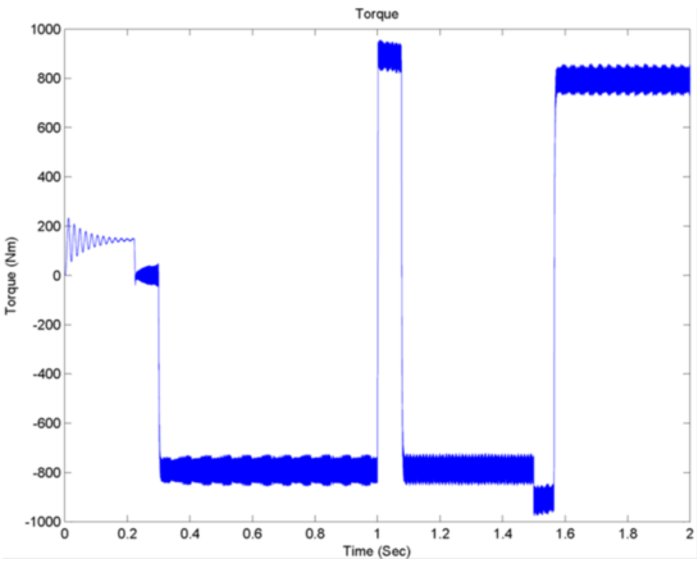


Fig. 13: Torque Response DTC Drive with Three-Level Inverter

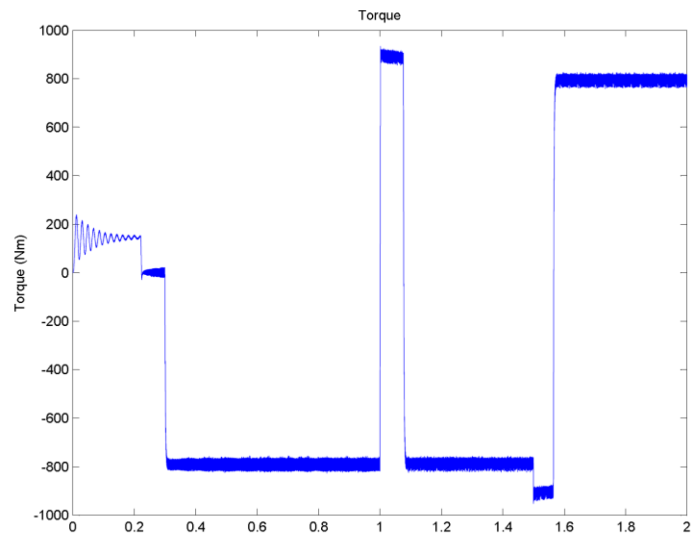


Fig. 14: Torque Response DTC Drive withFive-Level Inverter

The Fig. 13 shows the torque response of induction motor with Three Level PWM Inverter. It is seen that torque ripples are present. Fig. 14 shows the torque response of DTC drive with five level inverter. It is seen that there is reduction in torque rippleswith five level inverter. Thus as we go from three level to five level inverter in DTC drive there is reduction in torque ripples.

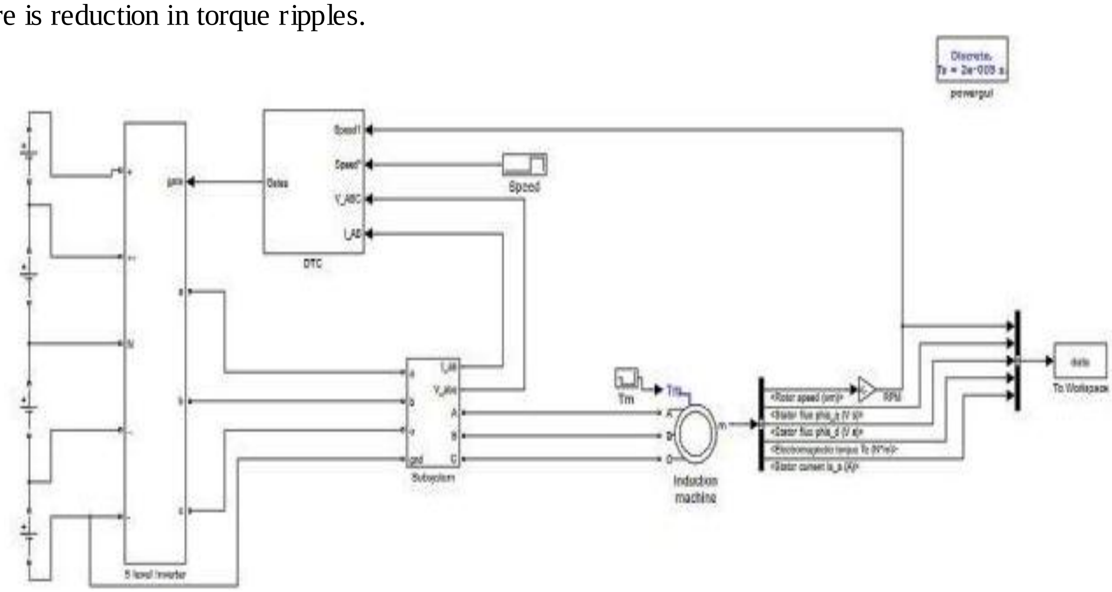


Fig. 15 MATLAB/SIMULINK Model of DTC Drive with Five Level PWM Inverter

VII CONCLUSION

High performance control of torque and flux both under steady state as well as dynamic condition is achieved by direct torque control method. Because of it simple structure and robustness against parameter variation it has become very popular method in motion control.

Further DTC with SVPWM technique reduces the inherent problems associated with direct torque control method like torque and flux ripples, hence it can be used in industrial applications where smooth and fine control of drive is essential.

This paper presents a very simple implementation of the direct torque control algorithm to be applied to 3-Level and 5 Level PWM inverters. The inverter topology used was diode clamped multilevel inverter. The simulation results obtained for the DTC SVM with five level inverter illustrate a considerable reduction in torque ripple and flux ripple compared to the three level PWM Inverter. Thus it is concluded that multilevel inverter synthesizes the staircase output voltage waveform, which is approaching to sinusoidal waveform, hence it is characterized with reduced torque and flux ripple, less distortion, less switching frequency, higher efficiency and use of low voltage rated switching devices.
The proposed direct torque control scheme with 3 Level and 5 Level Inverter can be extended to further higher-level inverters for torque and flux ripple reduction and hence obtain improved drive performance also artificial intelligence techniques like neural networks and fuzzy logic can be implemented .

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