Evaluation of Direct Torque Control for High-Power Induction Motor Drive

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Abstract

Direct Torque Control with Multilevel Inverter (DTC-MLI) has emerged recently in high dynamics AC drives fields for induction machines or permanent magnet machines application. Direct Torque Control (DTC) has the characters such as combined simplicity and robustness with excellent performance of torque control for the drive system. In this paper, DTC technique for drive system fed on three-level inverter and induction motor is presented, which means to select and compose right voltage vectors varying from speed working in constant torque area. The simulation results confirm that the control method is very effective with greater number of levels in the output voltage waveforms, lower dv/dt, less harmonic distortion and lower switching frequencies

1. Introduction

Induction machines have several advantages over DC machines. They are robust, require less maintenance, cheaper, and operate at higher speed. Basically, induction machines control methods can be classified into scalar and vector control. In scalar control, only magnitude and frequency of voltage, current, and flux linkage space vectors are controlled. Whereas, in vector control, the instantaneous positions as well as the magnitude and frequency of voltage, current, and flux linkage space vectors are controlled. Constant volt per hertz is a well-known scalar control method while Field Oriented Control (FOC) and Direct Torque Control (DTC) are the two most popular vector control methods.

Direct Torque Control was first introduced by Takahashi in 1986. The principle is based on limit cycle control and it enables both quick torque response and efficiency operation [3]. DTC control the torque and speed of the motor, which is directly based on the electromagnetic state of the motor [4]. It has many advantages compare to FOC, such as less machine parameter dependence, simpler implementation and quicker dynamic torque response. It only needs to know the stator resistance and terminal quantities (*v* and *i*) in order to perform the stator flux and torque estimations. The configuration of DTC is simpler than the FOC system due to the absence of frame transformer, current controlled inverter and position encoder, which introduces delays and requires mechanical transducer. In [1], Takahashi had proved the feasibility of DTC compared to FOC.

2. Principle of Direct Torque Control

The basic configuration of the conventional DTC drive proposed by Takahashi [1], which consists of a pair of hysteresis comparator, torque and flux estimators, voltage vector selector and a Voltage Source Inverter (VSI)

DTC performs separate control of the stator flux and torque, which is also known as decouple control. The core of this control method is to minimize the torque and flux errors to zero by using a pair of hysteresis comparators. The hysteresis comparators lie at the heart of DTC scheme not only to determine the appropriate voltage vector selection but also the period of the voltage vector selected. The performance of the system is directly dependent on the estimation of stator flux and torque. Inaccurate estimations will result in an incorrect voltage vector selection.

3. Three-Level Inverter Drive

A simulation on the conventional DTC drive is performed for better understanding by using MATLAB/SIMULINK. With the understanding and knowledge of the conventional DTC, three-level inverter is proposed for high power drives [3]. A conventional three-phase, two-level, and six-switch inverter is able to switch each phase between two voltages. These are the positive and negative rails of the DC bus. A three level inverter is able to produce a phase voltage consisting of three voltage levels (positive, negative, and zero).

By producing an output voltage having more levels, the inverter can better approximate the required sinusoidal output voltage. A better approximation of a sinusoidal voltage can be achieved for the same device switching frequency, which results in reduced current harmonics in the load [8]. For an induction motor these current harmonics cause increased copper losses, iron losses, torque pulsations, noise and mechanical stresses. The main difference between the conventional VSI and Multi-Level inverter varies with switching states which is shown in Table 1. The multi-level inverter has better edge in performance than former.

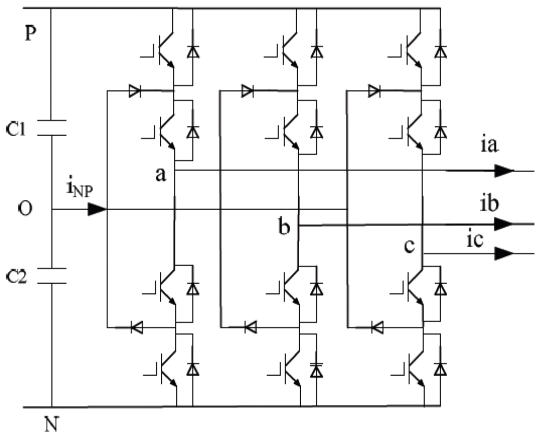

Figure 1. The topology of NPC three-level inverter

A three-level inverter causes lower losses in the induction motor and therefore results in a more efficient system. With three states (positive, zero, and negative) for each of the three phases, a total of 3^3(27) valid IGBT combinations can be produced. Each IGBT combination is represented as a mnemonic such as +, -, 0 that represents the voltage produced by each of the three phases. The phase-to-phase voltage applied to the load is either zero (both phases at the same state), half of the DC bus voltage (one phase at zero and the other either positive or negative), or the full DC bus voltage (one phase positive and the other negative).

4. DTC for Three-Level Inverter

A three-level inverter can generate at its output 27 different voltage vectors in the stationary reference frame as shown in Figure 3.3. Some of these voltage vectors can be generated by more than one switching state as listed in the second column of Table 1. In this table, the three digits of a switching state [k_a, k_b, k_J] denote the connection status of output phases of inverter, [a b c] to one of three poles of DC link, while the values 1, -1 and 0 represent their connection to positive, negative and neutral poles of DC link respectively. The third columns fourth columns of this table introduce the vector number and D3 components of inverter output voltage in stationary reference frame when the respective voltage vector is switched.

Table 1. Switch States of A Three-Level NPC Inverter

Switch States				
S_1	**S_2**	**S_3**	**S_4**	**Output Voltage**
ON	ON	OFF	OFF	+ 1\2 V_S
OFF	ON	ON	OFF	0
OFF	OFF	ON	ON	- 1\2 V_S

The control of torque, speed and the stator inactive power is realized by changing the frequency, amplitude, phase and phase order of the rotor voltages. The motor torque equation given in Eq(1) can be expressed as vector forms in the stator field-oriented α-β reference axes

$$T_e = \frac{3}{2} n_p \frac{L_m}{\sigma L_r L_s} \Psi_r \times \Psi_s \sin \theta_{sr} \quad (1)$$

Where, n_p is the number of poles,
Ψ_r , Ψ_s are respectively stator and rotor flux vectors,
L_s , L_r are respectively stator and rotor inductance,
L_m is the mutual inductance,
Θ_{sr} is the angle between the stator and the rotor flux Space vectors

For a constant magnitude of the stator and rotor flux space vectors, the angle Θ_{sr} may be used to control the torque of the motor. The following expression may be obtained from the stator voltage equation i.e. Eq(2)of the induction motor model.

$$\Psi = \frac{1}{T_n} \int_0^t V_s \quad (2)$$

Where, T_n denotes the constant electrical time and V_s denote the stator voltage space vector. This expression is valid for a stator fixed reference frame and a stator resistance equal to zero. It can be seen that the stator voltage directly impresses the stator flux. The stator voltage space vector V_s may assume twenty-four different non zero states and three zero states in NPC inverter as shown in Fig.2.

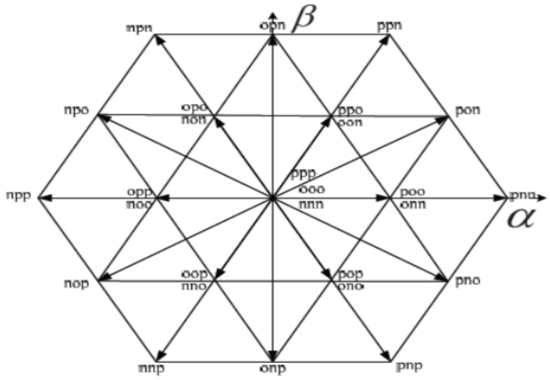

Figure 2. Distribution of three-level inverter space vectors

Figure 3 illustrates the layout of a typical DTC controller. Using the torque and flux error command, the controller selects a proper voltage vector from a predefined switching table to satisfy both flux and torque requirements simultaneously. It operates in such a way that the flux and torque errors do not exceed their limits known as hysteresis bands.

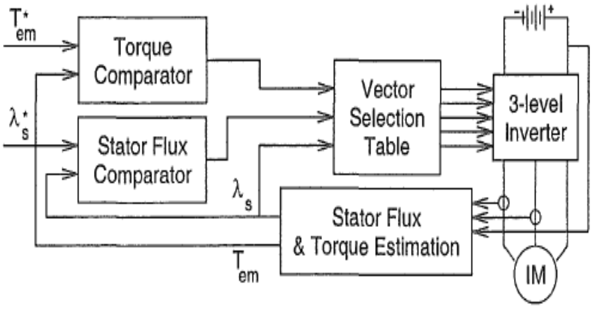

Figure 3. Typical Block Diagram of DTC Induction Motor Drive

The stator flux and motor torque are estimated from the measured stator voltage and current signals. In this method a suitable switching table is the most important part of the controller. It affects directly the drive performances. Thus, accurate knowledge about the affecting characteristic of voltage vectors is worthy and allows the designers to guarantee the best performance of the drive using voltage vectors with unchangeable affecting characteristic for each sector in the switching table.

5. Results

Simulations for both conventional and proposed three-level inverter drive are carried out using MATLAB/SIMULINK simulation package. A brief description of simulation method is given. The simulation results obtained are compared for verification. MATLAB/SIMULINK is a software package for modeling, simulating and analyzing dynamic systems. Figure 4 illustrates the complete model of DTC drive, which consists of an induction machine, stator flux and torque estimators, torque and flux controllers, flux orientation, voltage vector selector and Three-Level inverter

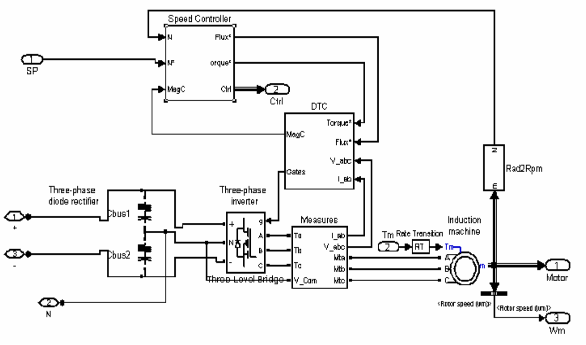

Figure 4. Matlab Modeled DTC Drive

The steady-state performance of the Direct torque control schemes is evaluated based on the torque and speed response. From the Fig.5 , initial speed response for 500 rpm was achieved in 0.6 sec and second setting of speed reference 0f 1000 rpm which was set at 1.5 sec reached steady state at 2.1 secs

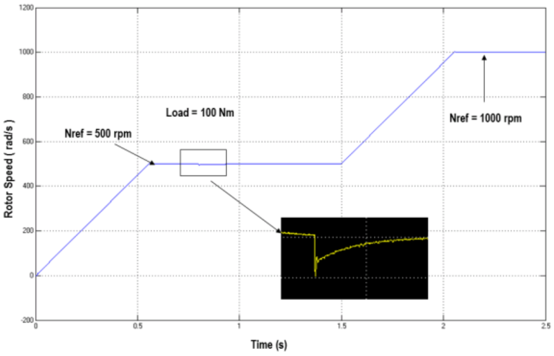

Figure 5. Speed Response of the DTC

Torque Response: Initially condition of motor is no load condition. In order to reach the initial speed reference, DTC system has generated reference torque of 40 NM. At 0.6 sec, motor has reached the reference speed of 500 rpm and torque generated is zero from 0.6 sec. At 0.8 sec, load torque of 100nm is added and response time for DTC system to reach is minimal. This proves the dynamic response of DTC system for transient conditions. At 1.5 sec, reference speed is changed to 1000 rpm and change in generated torque changed to 140 nm to obtain 1000 rpm. Once the motor reached reference speed 2.1 sec, torque generated is 100 nm. The description above is illustrated in Fig.6.

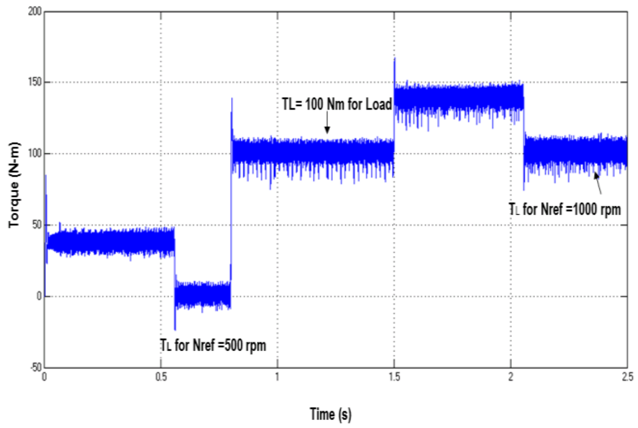

Figure 6. Torque Response of the DTC

7. Observations

Fig.7 illustrates the dv/dt effect through stator voltage waveform, which gives clear picture of voltage level which jumps from E to –E, which is unusual with multi-level inverter output. Fig.8 shows the variation in the neutral point voltage.

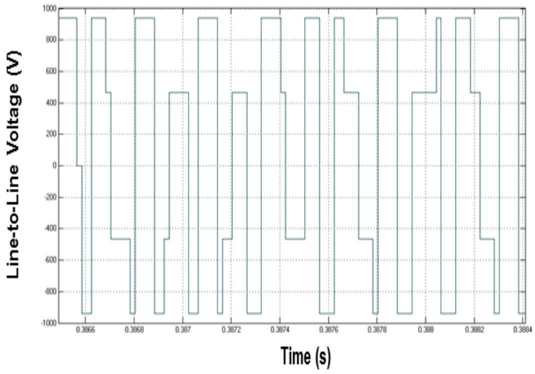

Figure 7. Illustration of dv/dt stress on Switches

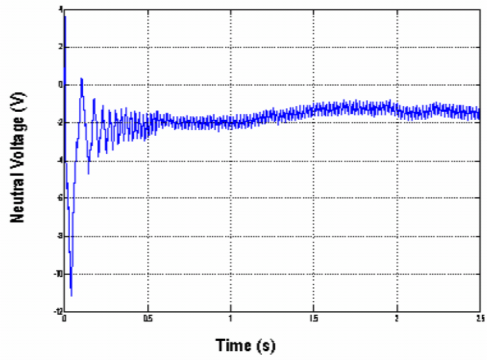

Figure 8. Illustration of Neutral Point Variation

8. Conclusion

The main contribution of this paper is to propose a three-level inverter based DTC system that significantly reduces torque and stator flux ripples. At the same time demerits of the system when applied to three-level inverter were found. • It states the advantages of Three-Level inverter drive stated and also points out main issues like dv/dt stress and neutral point voltage variation

10. References

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