Journal of Theoretical and Applied Information Technology
31st July 2012. Vol. 41 No.2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

DIRECT TORQUE CONTROL OF MULTILEVEL INVERTER-FED INDUCTION MACHINES – A SURVEY

[1]NAZIHA AHMAD AZLI, [2]NORJULIA MOHD NORDIN, [3]NIK RUMZI NIK IDRIS
Universiti Teknologi Malaysia, Faculty of Electrical Engineering, Department of Energy Conversion, UTM Skudai, Johor, Malaysia
E-mail: [1]naziha@ieee.org, [2]norjulianordin@ieee.org, [3]nikrumzi@ieee.org

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. In this paper, a review on a variety of techniques and concepts of direct torque control of multilevel inverter-fed induction machines is presented. The techniques and concept involved are classified as follows: Look-up table hysteresis based DTC-MLI, DTC-MLI with space vector modulation, predictive control strategy of DTC-MLI, hybrid modulation and hybrid inverter strategy of DTC-MLI and DTC-MLI with fuzzy logic controller. From this review, the properties of the discussed controller techniques together with advantages and disadvantages are presented.

Keywords: *Direct Torque Control (DTC), multilevel inverter, look-up table, Space Vector Modulation (SVM), predictive, Fuzzy Logic Controller (FLC)*

1. INTRODUCTION

Induction Machines (IMs) have been widely used in the industry due to the fact that it is maintenance free, simple in terms of construction, reliable and rugged. In contrast to the commutation DC motors, induction machines can be used in an explosive, corrosive or any harsh environment. This is because the latter has no problem with spark and corrosion which is due to the commutator and the brushes as in the former. Despite these advantages, IM however, suffers from control problems when used in high performance Adjustable Speed Drive (ASD) applications. Based on the commonly adopted space phasor dynamics model [1-3], equations related to the dynamics modeling of an IM are :-

$$\overline{{}^{G}v_s} = R_s \overline{{}^{G}i_s} + \frac{d\overline{{}^{G}\psi_s}}{dt} + j\omega_G \overline{{}^{G}\psi_s} \tag{1}$$

$$0 = R_r \overline{{}^{G}i_r} + \frac{d\overline{{}^{G}\psi_r}}{dt} + j(\omega_G - \omega_r)\overline{{}^{G}\psi_r} \tag{2}$$

$$\overline{{}^{G}\psi_s} = L_s \overline{{}^{G}i_s} + L_m \overline{{}^{G}i_r} \tag{3}$$

$$\overline{{}^{G}\psi_r} = L_r \overline{{}^{G}i_r} + L_m \overline{{}^{G}i_s} \tag{4}$$

$$T_e = \frac{3}{2} P \overline{{}^{G}\psi_s} \times \overline{{}^{G}i_s} \tag{5}$$

$$T_e - T_L = J\frac{d\omega_m}{dt} = \frac{J}{P}\frac{d\omega_r}{dt} \tag{6}$$

where $\boldsymbol{v_s}$, $\boldsymbol{\psi_s}$, $\boldsymbol{\psi_r}$, $\boldsymbol{i_s}$ and $\boldsymbol{i_r}$ are the stator voltage, stator flux, rotor flux, stator current and rotor current vectors respectively; ω_r and ω_m are the rotor speed in rad/s and mechanical speed in rpm; L_s, L_r and L_m are the stator, rotor and magnetizing inductances; T_e, T_L,J and P are the electromagnetic torque, load torque, system inertia and the number of pole pairs, respectively. These space phasor quantities are expressed in the general reference frame which rotates at a general speed, ω_G. The super-script 'G' denotes that the quantities are in the general reference frame.

Controlling IM is considerably more complex than that of DC machines. There are several ways of controlling IM. It can be classified into two general control methods; *Scalar* and *Vector Control*. In scalar control, only the magnitude and frequency, which is based on the steady state model of IM of a space vector variable such as current, voltage and flux linkage, are controlled. Contrarily, in vector control, the torque developed in the motor together with the magnitude and frequency of space vectors of three-phase motor variables are manipulated in the control algorithm. These space

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

vectors represent the instantaneous values of the corresponding three-phase variables which are based on an IM dynamic model.

Various methods have been discovered to implement vector control for IM. One of the well-known vector control method is Field Oriented Control (FOC) that has been proposed by F. Blaschke [4] and K. Hasse [5] This type of control is rotor-flux oriented based which means the rotor flux vector is the orienting vector of the controller. This method enables IM to emulate the separately excited DC machines and gives it high dynamic performance. In FOC, the position sensor is employed for coordinate transformation of the IM equations. FOC can be divided into two types; Direct and Indirect.

In the case of Direct FOC (flux-feedback control), the rotor flux linkage vector is determined by direct measurement of the air-gap flux. It is the only parameter that can be measured directly from the motor (using a Two Hall sensor or search coils or tapped stator windings of the machine [2]) together with the stator current and calculated directly by a so-called flux model. For Indirect FOC (flux-feedforward control), the rotor flux linkage vector is determined indirectly by utilizing the monitored stator current and rotor speed. The rotor flux linkage angle that is used in the coordinate transformation is obtained as a sum of the rotor angular position that is measured by a shaft position sensor and the slip angular position.

Other than rotor-flux oriented based, FOC can be controlled based on stator-flux orientation which is known as Stator Flux Oriented Control (SFOC) [6]. In contrast to the rotor-flux FOC, SFOC does not require the knowledge of rotor speed. Instead, only the stator resistance, voltage and current values are required. Therefore it is more robust to parameter variations and easier to implement [7].

In early 1980s, an innovation on FOC has been made by Isao Takahashi and Noguchi [8] and Depenrbrock [9] in which case the coordinate transformation block is omitted. The block is replaced with the bang-bang or hysteresis controller [1] for the developed torque and stator flux. In addition, the approach in controlling the inverter is clearly different from that of FOC. This control strategy is referred to as Direct Torque Control (DTC). DTC has been experiencing continuous improvement and further development by many other researchers throughout the years. The 1990s sees the emergence of technologies that require higher level of power and voltage. Multilevel inverters have then been highlighted as the solution at such level of operation. Multilevel inverters are known to offer several advantages such as very low harmonic distortion, low *dv/dt*, no output filter requirement etc. [10]. Due to the continuously evolving industrial applications that need high power and voltage operating level as well as high performance of machines applications, researchers have proposed to extend or adapt the traditional DTC scheme to multilevel inverter topologies. This means that the multilevel inverters are replacing the conventional three-phase inverters that have been previously used in the traditional DTC configuration to supply the stator voltage for the IM.

This paper presents a review on the development and improvement of DTC with multilevel inverter control techniques for IM. The basic concept of conventional DTC and DTC-MLI are given in Section 2. Various techniques and concepts of DTC-MLI such as look-up table strategy space vector modulation strategy, predictive strategy, hybrid strategy and fuzzy logic strategy are discussed from sections 3 to 7 respectively, before forwarding the conclusion of the review.

2. DTC BASIC CONCEPT

Fig. 1 shows the general DTC block diagram. The instantaneous values of flux and torque are calculated from the measured variables of the IM and directly controlled by selecting an optimum switching state of the inverter so that the required

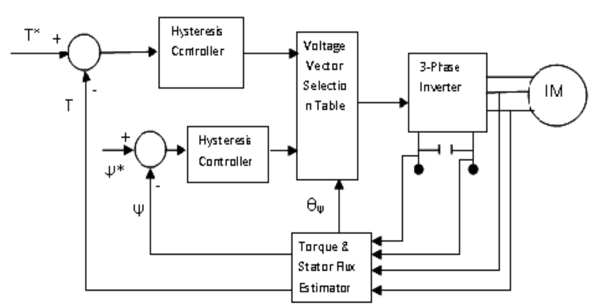


Fig. 1. General DTC block diagram

optimum voltage vector is generated.

In stationary reference frame, the stator voltage vector as in (1), can be written as,

$$\overline{v_s} = R_s \overline{i_s} + \frac{d\overline{\psi_s}}{dt} \qquad (7)$$

Journal of Theoretical and Applied Information Technology
31st July 2012. Vol. 41 No.2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

If it is assumed for over a small period of time and the voltage drop across the stator resistance can be neglected, (7) can be rewritten as,

$$\overline{v_s} = \frac{\Delta\overline{\psi_s}}{\Delta t} \tag{8}$$

which clearly shows that the variation of stator voltage vector is directly affected by the stator flux linkage vector. Thus the stator flux locus can be controlled by selecting the appropriate voltage vector. In DTC scheme, the radius of the locus which is also known as the stator flux magnitude is forced to follow a circular path by limiting its magnitude within the hysteresis band. When the stator flux touches the upper or the lower hysteresis band, an appropriate voltage vector is selected either to decrease or increase the stator flux magnitude, respectively. Contrarily, variation of the stator voltage over the rotor flux linkage is filtered by the rotor and stator leakage inductances. Therefore over a small period of time, the rotor flux is assumed to have a slower rotation compared to the stator flux. For that reason when the voltage vector is applied, the stator flux will have a quick movement. Hence the angle between both flux vectors, θ_{sr} will increase and that will cause an increase in the electromagnetic torque, T_e. The relations between the stator-rotor flux angle and the electromagnetic torque can be expressed as

$$T_e = \frac{3}{2}P\overline{\psi_s}\times\overline{i_s} = \frac{3}{2}P|\psi_s||\psi_r|\sin\theta_{sr} \tag{9}$$

where $|\psi_s|$ and $|\psi_r|$ are the magnitude of stator flux linkage and the magnitude of rotor flux linkage respectively and this expression is in the stationary reference frame. In other words, the variation of the stator voltage will affect both stator flux and stator-rotor angle movement. This principle is used in DTC to achieve the desired torque response and to correct the flux trajectory of the induction machines.

A. DTC with Multilevel Inverter (DTC-MLI)

When a multilevel inverter is used in the DTC configuration to feed the IM, the number of available voltage space vectors is increased proportionally to the voltage levels of the inverter. By having this extra flexibility in selecting the optimum voltage vector, a more precise control of both torque and flux can be obtained. To feed a three-phase IM, a three-phase multilevel inverter is required. The three-phase multilevel inverter is composed of three multilevel inverter legs.

There are three prominent multilevel inverter topologies: Diode-clamped multilevel inverter (DCMI) or neutral-point clamped (NPC) inverter, Flying Capacitor multilevel inverter (FCMI), and Cascaded H-Bridge multilevel inverter (CHMI).

Fig. 2 (a), (b), and (c) show one of the three multilevel inverter legs that are required in feeding a three-phase IM.

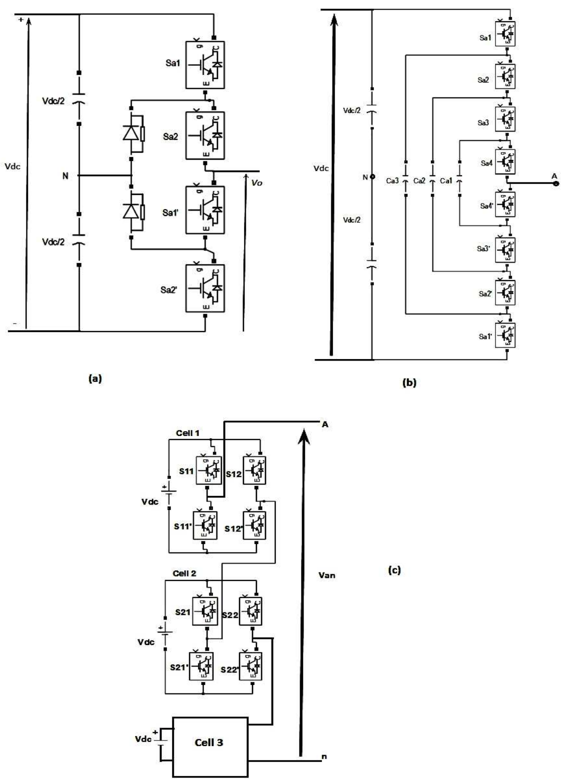


Fig. 2. Multilevel inverter leg for single phase. (a) Neutral-point Clamped (NPC) topology (b) Flying Capacitor (FCMI) topology (c) Cascaded H-Bridge

In Fig. 3 the general block diagram of a three-phase IM fed by a three-phase multilevel inverter is shown. The control strategy block generates the appropriate voltage vector in order to keep the reference (torque, speed or position) at the right values. Fig. 4 (a), (b), and (c) show a set of voltage space vectors that can be generated by an NPC inverter, FCMI, and CHMI respectively. By injecting the required value of the voltage vector to the inverter control block, the switching state is generated accordingly for each multilevel inverter legs.

Journal of Theoretical and Applied Information Technology
31st July 2012. Vol. 41 No.2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

Several control strategies have been proposed for DTC-MLI such as look-up table strategy (LUT), space vector modulation strategy (SVM), predictive control strategy, fuzzy logic control strategy (FLC) and hybrid control strategy. The details of these controllers are described in the following section.

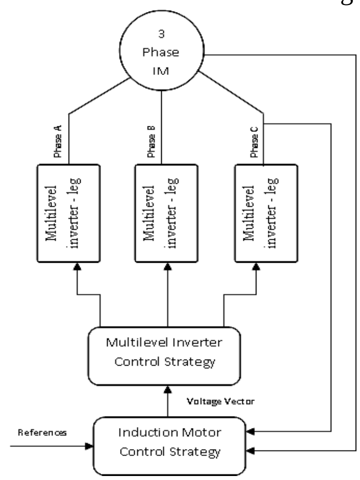


Fig. 3. General block diagram of three-phase IM fed by three-phase multilevel inverter

3. LOOK-UP TABLE STRATEGY OF DTC-MLI (LUT-DTC)

A general block diagram for DTC with Look-up Table (LUT-DTC) is shown in Fig. 5.

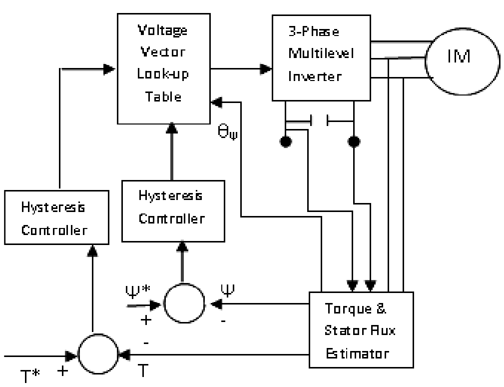
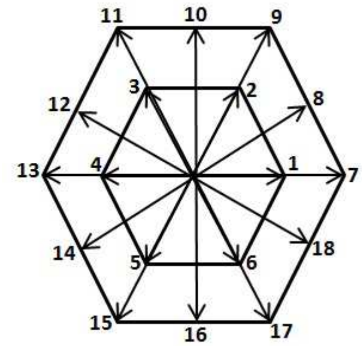
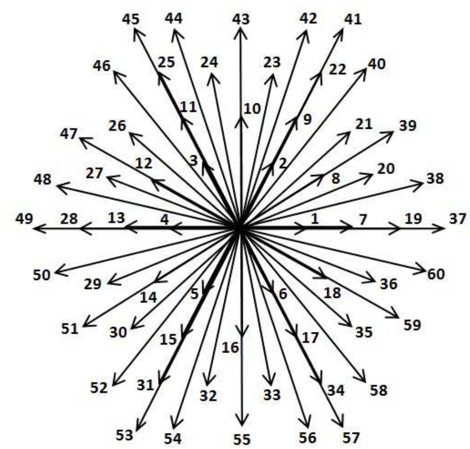


Fig. 5. General block diagram for DTC with look-up table strategy (DTC-LUT)

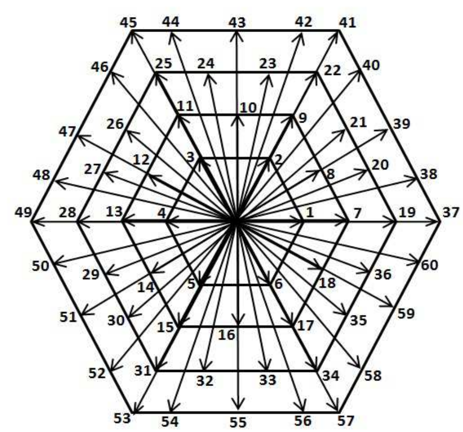
The stator flux, ψ_s* and torque, T_e* reference is compared to stator flux, ψ_s and torque, T_e by using the flux and torque hysteresis controller, respectively. In the classical DTC which uses a conventional three-phase inverter, the d-q flux plane is divided into 6 sectors. The flux and torque



(a)



(b)



(c)

Fig. 4. Set of voltage vector that can be generated by multilevel inverter topology. (a) 3-level Neutral-point Clamped (NPC) topology (b) 5-level Flying Capacitor (FCMI) topology (c) 5-level Cascaded H-

Journal of Theoretical and Applied Information Technology
31st July 2012. Vol. 41 No.2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

hysteresis controller consist of two- and three-level comparator respectively that generate the digitized output signal which can be defined as,

$$\psi_{error} = 0 \quad \text{for} \quad \psi_s^* - \psi_s > H_{\psi,upper}$$
$$\psi_{error} = 1 \quad \text{for} \quad \psi_s^* - \psi_s < H_{\psi,Lower}$$

for flux and

$$T_{error} = -1 \quad \text{for} \quad T_e^* - T_e > H_{T_e,upper}$$
$$T_{error} = 0 \quad \text{for} \quad T_e^* - T_e = 0$$
$$T_{error} = 1 \quad \text{for} \quad T_e^* - T_e < H_{T_e,Lower}$$

for torque, where ψ_{error} and T_{error} is the stator flux and electromagnetic torque error; $H_{\psi,upper}$, $H_{\psi,Lower}$, $H_{T,upper}$, $H_{T,Lower}$, are the flux and torque hysteresis upper and lower band, respectively.

However when DTC is adapted or extended to the multilevel inverter, the hysteresis controller need to be modified to suite the multilevel inverter topology. Adaptation of DTC on a FCMI or NPC inverter is presented in [11] and [12]. In both cases, the d-q flux plane is divided into 12 sectors. But when it comes to selecting the appropriate voltage vector to correct the actual flux and torque, different approaches have been proposed.

In [11], balancing of the neutral-point voltage needs to be taken into account when selecting the voltage vector. Therefore the virtual vectors concept which employs an optimum look-up table for a switching strategy has been adopted in selecting the suitable voltage while at the same time the neutral-point voltage is remained balanced. In the virtual vectors concept, a similar hysteresis control as the classical DTC is employed.

. On the contrary, in [12], the flux control is composed of a two-level hysteresis comparator that is defined in three regions; Negative Flux error, Zero Flux error, and Positive Flux error. As for the torque control, it employs a five-level hysteresis comparator that is defined in five regions; Negative Large Torque error, Negative Small Torque error, Zero Torque error, Positive Small Torque error, and Positive Large Torque error. For the switching strategies, two different approaches have been proposed. Thus, based on12 sectors in the d-q flux plane, two types of switching table where by each of it holds one approach are developed.

Similar to the NPC inverter, the switching strategy in an FCMI as presented in [13] must be capable of balancing the capacitor voltage and the required voltage levels. In the FCMI switching strategy, the d-q flux plane is divided into 12 sectors with the mechanical rotor speed taken into consideration in the voltage vector selection. Therefore, four switching tables are used. Each table corresponds to the specific range of rotor speed. When the speed is lower, low amplitude voltage vector is selected while at higher speed, high amplitude of voltage vector is selected. In this switching table, flux and torque are identified using 3 different states; ‘0’ means the flux and torque is within the limits of the hysteresis controller, ‘1’ means the values are greater than the upper limits; and ‘-1’ means the values are smaller than the lower limits.

4. SPACE VECTOR MODULATION STRATEGY OF DTC-MLI (DTC-SVM)

The use of a hysteresis comparator in classical DTC is known to cause variations in switching frequency that is undesirable since it can lead to dynamics resonance excitement in the load and hence constitute a serious drawback to DTC. This is because; the switching frequency is a function of motor speed, stator and rotor fluxes, and stator voltage which always vary with time. In addition the inverter switching capability is not fully utilized and also results in current and torque distortion due to sector change [14, 15].

A combination of DTC and Space Vector Modulation (SVM) avoids the use of look-up tables in selecting the voltage vector. SVM is used to synthesize a required voltage vector that has been calculated by the controller in the DTC scheme. By using a space vector modulator, the torque ripple is reduced and the switching frequency of the component is constant. When extending the classic DTC-SVM scheme to the multilevel inverter, some modifications have been made since the inverter is capable of generating more available voltage vectors proportional to its voltage levels.

A. Phase-Shifting SVM Strategy of DTC-MLI

In the Phase-Shifting SVM (PSSVM) strategy as proposed in [16], a CHMI has been employed. An N-cell cascaded H-bridge multilevel inverter (CHMI) generally has 2N arm vectors per phase with N left arm vectors and N right arm vectors. The output voltage vector, $\boldsymbol{U}$, of the inverter is defined as,

$$\boldsymbol{U_i} = \boldsymbol{U_{Li}} - \boldsymbol{U_{Ri}} \quad (10)$$

Journal of Theoretical and Applied Information Technology
31st July 2012. Vol. 41 No.2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

where $\boldsymbol{U_{Li}}$ and $\boldsymbol{U_{Ri}}$ are the total left and right arm voltage vectors of phase i (i = a, b, c) respectively. As for the N-cell CHMI, $\boldsymbol{U_{Li}}$ and $\boldsymbol{U_{Ri}}$ are defined as,

$$\boldsymbol{U_{Li} = U_{L1i} + U_{L2i} + U_{L3i} + \ldots + U_{LNi}} \qquad (11)$$

$$\boldsymbol{U_{Ri} = U_{R1i} + U_{R2i} + U_{R3i} + \ldots + U_{RNi}} \qquad (12)$$

The vectors $\boldsymbol{U_{Li}}$ and $\boldsymbol{U_{Ri}}$ for each cell are generated based on the SVM strategy of traditional two-level inverters. This SVM strategy decomposes the desired generated vector into two vectors with the same amplitude but different phase. By assuming the sampling period of the SVM is T_s, if four-part of modulating strategy is adopted, the phase shifting time of each cell is T_s/N, and if seven-part of modulating strategy is adopted, the phase shifting of each cell is $T_s/2N$. The effecting time of the left arm or the right arm vector of each cell is the same as the sampling time. Therefore the phase shifting time as mentioned earlier is the phase difference between the H-bridge vectors. To calculate the vector amplitude, the phase difference can be neglected since the sampling time period is commonly short. Hence the amplitude of every

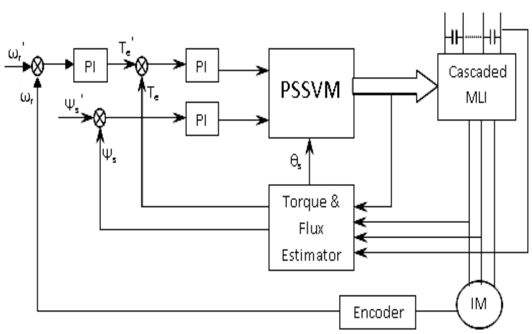


Fig. 6. DTC block diagram with PSSVM strategy

vector can be expressed as,

$$|U_{Li}| = |U_{Ri}| \approx \frac{1}{2N}|U_i| \qquad (13)$$

Fig. 6 shows the block diagram of the PSSVM-DTC.

B. Nearest Voltage Vector Strategy of DTC-MLI

The Nearest Voltage Vector strategy is another further modification of the SVM technique. This approach is close to DTC-SVM with closed-loop flux and torque control. In this strategy, the desired voltage that has been generated by the flux and torque controller is synthesized by choosing the nearest voltage vector that can be delivered by the multilevel inverter. There are two types of nearest voltage vector strategy. The first one is the nearest voltage vector that is determined by means of calculating the minimum distance of the voltage vector that can be generated by the multilevel inverter, which in this case the NPC inverter is used. This strategy has been proposed by X. del Toro Gracia et al [17].The second strategy is determining the closest or nearest voltage level instead of the nearest voltage vector. This strategy has been proposed by Kouro et al [18] and an asymmetry CHMI has been used. In this strategy, the reference voltage vector is transformed into a three-phase voltage reference in time domain using a three-phase coordinate transformation. Then by using the *round{x}* function, where x is the voltage reference, the voltage reference is rounded to the nearest integer. In this case the nearest integer is the nearest voltage level that can be delivered by the multilevel inverter.

5. PREDICTIVE CONTROL STRATEGY OF DTC-MLI

A predictive controller is one of the control algorithms that uses the foreknowledge of a system to predict the next state of a system which is the so-called one-step ahead prediction [19]. In electrical drives point of view, predictive control is based on the fact that the switching behavior of an inverter can be predicted. In addition, mathematical equations can be used to express the responses of the drive to determine a certain switching state. Hence the cascaded structure of the controller in the previous DTC control schemes can be eliminated as all of the measured system variables can be considered in one controller. Therefore the predictive controller offers a better dynamic performance and a better representation of a non-linear system.

There are a numbers of papers that report the application of predictive control in DTC with multilevel inverter schemes. Different predictive algorithms have been introduced in meeting specifications of reduced torque ripple and constant switching frequency.

A. DTC-MLI with Imposed Switching Frequency Strategy

In the literature, three types of multilevel inverters have been used in DTC with Imposed

Journal of Theoretical and Applied Information Technology
31st July 2012. Vol. 41 No.2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

Switching Frequency strategy; FCMI [20], CHMI [21], and asymmetry/hybrid CHMI [22]. In general, the switching frequency imposition strategy is performed by taking into account the instantaneous values of torque and flux and their derivatives for the selection of space vector. A predictive model is determined by deriving the estimated values of torque and flux, which are calculated from the measured values of IM variables, versus time. Considering at the sampling instant, t^k, the actual space vector position is Q^k. By using the knowledge

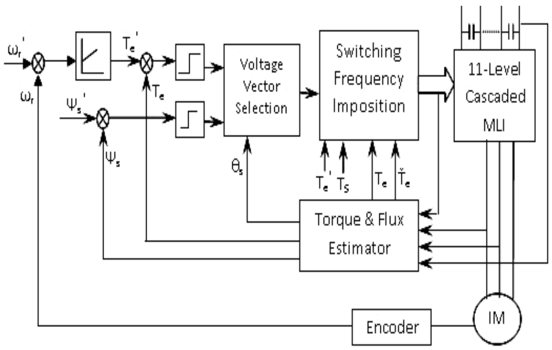


Fig. 7. General DTC block diagram with imposed switching frequency strategy

on the actual position, Q^k, and also from the torque and flux and their derivatives, the next point of the space vector position, Q^{k+1} can be obtained. In the same sampling instant, t^k the commutation time $t^k{}_{com}$ that will ensure the zero torque and flux error on the next sampling time is calculated. The Q^{k+1} is applied at $t^k{}_{com}$. Fig. 7 shows the general block diagram of DTC with imposed switching frequency.

B. DTC-MLI with PI and Dead-beat Controller

The combination of a PI controller and a dead-beat controller has been shown to improve both steady state and dynamic behavior of DTC-MLI [23]. The difference between the reference torque and the estimated torque is the input for the PI controller to obtain the slip angle variation (stator and rotor flux angle difference), $\Delta\theta_{12}$. As the PI controller can only offer a moderate dynamic performance, a dead-beat controller is employed to give a faster dynamic response. This is possible by predicting the slip angle variation using the value of the reference torque as given by (14) and preloading the PI controller part in the next sampling time.

$$\theta_{12}(t_{k+1}) = \arcsin\left(\frac{2}{3}\frac{T_e^*(t_{k+1}).\sigma.L_1 L_2^{'}}{p.L_h\psi_1^*(t_{k+1}).\psi_2^{'}(t_k)}\right) \tag{14}$$

where ψ_1* and T_e* are the stator flux and torque reference respectively; L_1, L_2' and L_h are stator, rotor, and mutual inductance respectively; σ, p, and ψ_2' are leakage factor, number of pole pairs and rotor flux referred to the stationary reference frame respectively. Thus, the output of the dead-beat controller is obtained as follows.

$$\Delta\theta_{12}(t_k) = \theta_{12}(t_{k+1}) - \theta_{12}(t_k) \tag{15}$$

By using the knowledge of a variation angle of rotor flux, $\Delta\theta_2$ as a feed-forward [23], which can be calculated by using a measured value of the machine, and the slip angle variation, the stator flux variation angle is determined by the following equation.

$$\Delta\theta_1(t_k) = \Delta\theta_{12}(t_k) + \Delta\theta_2(t_k) \tag{16}$$

Finally the appropriate stator voltage space phasor can be obtained by using the knowledge on the stator flux variation angle and the estimated stator flux linkage. This voltage space phasor then need to be synthesized to switching states using a modulator in order to ensure the multilevel inverter produces the appropriate voltage output. As in [23], this predictive control strategy for DTC has been adapted to the CHMI topology. Hence the space phasor modulator (SPM) has been considered to synthesize the voltage space phasor.

C. Output Regulation Subspace (ORS) based of Switching Control for DTC-MLI Schemes

The use of the Output Regulation Subspace (ORS) concept which introduces a hyperplane that partitions the input space and a quadratic criterion is one of the further improvements of the predictive control concept. The incorporation of these concepts has been shown to assist in the reduction of the computational load [24]. Adapting a classical DTC scheme with the controller concept as mentioned earlier, avoids the use of look-up table, guarantees the regulation task and reduces the torque ripple. In the middle of 2003, this method has been adapted to DTC with an NPC inverter in selecting the voltage vectors [25]. In this application, ORS defines two straight lines that divide the vector space (input space) plane into four quadrants corresponding to different combination of signs for torque and flux time derivatives. Both

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

ORSs (torque and flux) are perpendicular and intersect each other at the origin. Therefore it is found to reduce the space where the vectors are selected. In other words, the search of suitable voltage vector is restricted to a certain quadrant. Hence it reduces the mathematical computation while evaluating them in energy function.

6. HYBRID MODULATION AND HYBRID INVERTER CONFIGURATION STRATEGY OF DTC-MLI

The development in the improvement of DTC performance not only focuses on seeking for new solutions in the multilevel inverter switching control strategy but also in the configuration of the multilevel inverter itself. In [26], a hybrid modulation strategy has been proposed for DTC with asymmetric CHMI. The DTC scheme is accomplished by using a torque error (the difference between the reference torque and the estimated torque) to generate a reference load angle, δ^*, which is necessary to correct the torque behavior. Then the desired load angle is used to produce an appropriate stator flux reference which is determined by,

$$\psi_s^* = |\psi_s^*| \cos(\delta^* + \theta_r) + j|\psi_s^*| \sin(\delta^* + \theta_r) \qquad (17)$$

where $|\psi_s^*|$ is the stator flux reference amplitude and θ_r is the rotor flux vector angle. By subtracting the stator flux reference with the estimated stator flux, a variation of stator flux ($\Delta\psi_s$) is obtained. Then the appropriate voltage vector is determined as follows,

$$v_s^* \approx \frac{\Delta \psi_s}{T_s} \qquad (18)$$

The appropriate voltage vector is then synthesized by the hybrid modulation strategy to produce a switching state for the multilevel inverter. This type of modulation strategy helps to reduce switching losses and improve the converter efficiency since the highest power cell needs only 4 commutations per reference cycle, which means that the switches turn ON and OFF only once during a half cycle. The un-modulated part left by the square shape of the highest power cell output is then modulated by the next power cell and so on until the final un-modulated part of the reference is modulated by the smallest power cell at high switching frequency using PWM. This modulation strategy then produces a multilevel stepped waveform with a high frequency component but lesser switching losses in producing it. Fig. 8 shows a hybrid modulation operating principle for a 3 cell asymmetric CHMI

As proposed in [27], a modified three-phase cascaded of two inverters has been used in DTC implementation. Fig. 9 shows the configuration of a modified three-phase inverter in cascaded topology. The new inverter topology as in Fig. 9 can produce a maximum of 9 levels or 11 levels of output voltage depending on the correlation between the voltage of isolated sources, $\mathbf{U_d}$, $\mathbf{U_{d1}}$, $\mathbf{U_{d2}}$, and $\mathbf{U_{d3}}$.

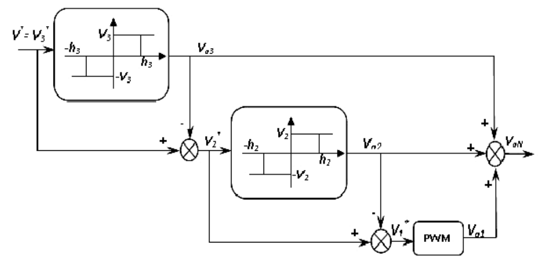


Fig. 8. Hybrid modulation operating principle for 3 cell asymmetric cascaded multilevel inverter

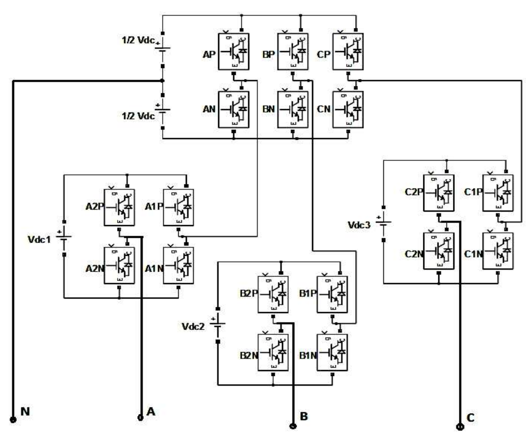


Fig. 9. Modified three-phase inverter

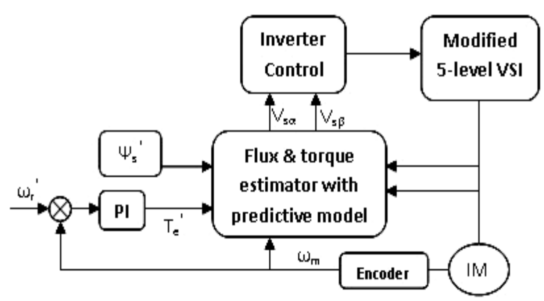


Fig. 10. DTC system fed by modified multilevel inverter block diagram

In this case, a DTC scheme is performed by using a

Journal of Theoretical and Applied Information Technology
31st July 2012. Vol. 41 No.2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

predictive model of IM together with the flux and torque estimator to obtain an optimal stator voltage vector as a function of torque and stator flux, $V_{s\alpha}^{opt}$ and $V_{s\beta}^{opt}$, in α and β plane respectively. From this optimal voltage vector, the closest voltage vector that may be delivered by the modified multilevel inverter is chosen through the switching function algorithm in an inverter control block. Fig. 10 shows a DTC system fed by the modified multilevel inverter as proposed in [27].

7. DTC-MLI WITH FUZZY LOGIC CONTROLLER

The employment of Fuzzy Logic Controller (FLC) in DTC has provided some improvements in torque and stator flux control and switching

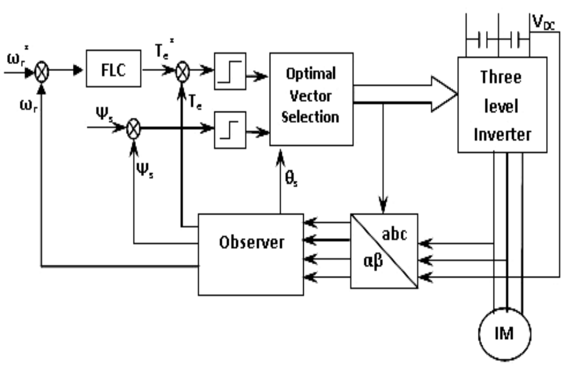


Fig. 11. Block diagram for the DTC scheme with FLC at the outer speed loop

frequency [28]. In the literature, FLC can be either added to one part of the DTC-SVM scheme [29] or replacing the hysteresis controller and the look-up table used in DTC-LUT [30] for switching synthesization and neutral-point-voltage balance since a 3-level NPC inverter is used. As in [31], the FLC is located at the outer speed loop and some modification has been made in vector selection such as introducing 2 types of DTC with FLC algorithm in one system in order to suite it with the SVM method. Fig. 11 shows the block diagram of the DTC scheme with FLC at the outer speed loop.

As in [29], the FLC is added to both the hysteresis controller and the torque and stator flux. By using this modification, the hysteresis cycle becomes wider. It provides a more precise selection of the voltage vector, hence enhancing the performance of torque and stator flux control in a DTC and neutral-point-balance in the NPC inverter. Fig. 12 illustrates the modification of the DTC

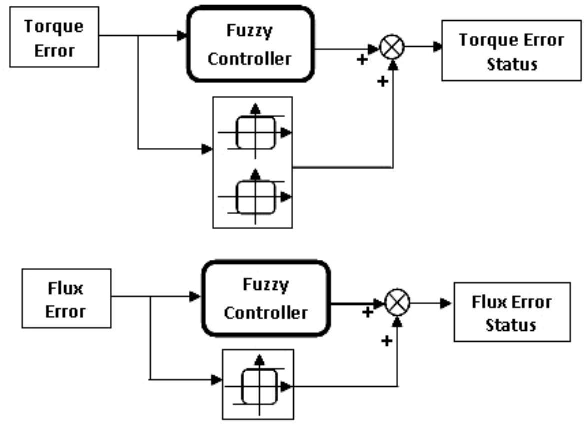


Fig. 12. Hysteresis Controller with additional fuzzy controller

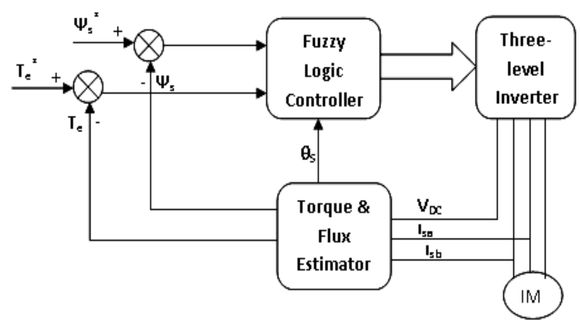


Fig. 13. Block diagram for the DTC scheme with fuzzy logic controller

conventional hysteresis controller. Fig. 12 illustrates the modification of DTC hysteresis controller.

In [30], the hysteresis controller and the look-up table has been replaced by FLC. The switching state selections were done by FLC. Some modification has been made to the look-up table in order to suite it with the FLC rules. By using this scheme, the DTC performances are enhanced in terms of reducing flux and torque ripples, and harmonic distortion. Fig. 13 shows the block diagram of DTC system with FLC.

8. CONCLUSION

In this paper, a theoretical review on DTC strategies with multilevel inverter for induction machines has been presented. DTC is a viable alternative solution to FOC in AC drive. It is known to offer a simple configuration of DTC due to the absence of coordinate transformation block. It is also capable of performing with both fast torque response and harmonics reduction. However this classic DTC scheme has some disadvantages such as high torque ripple, variable switching

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

frequency and harmonic losses which are still considered as high. Adapting DTC to multilevel inverters is one of the improvements that can be made for fast torque response during transient, torque ripple reduction, constant switching frequency operation and lower harmonics losses. This is because a multilevel inverter offers a nearly sinusoidal voltage output, lower *dv/dt*, and extra degrees of freedom in voltage vector selection in order to ensure the minimization of torque and flux ripple.

DTC strategies with multilevel inverters have been divided into five groups: switching table (look-up table) strategy of DTC-MLI, space vector modulation strategy of DTC-MLI, predictive control strategy of DTC-MLI, Hybrid modulation and hybrid inverter configuration strategy of DTC-MLI and FLC strategy of DTC-MLI. The basic principle, advantages and limitation of each strategy has been systematically presented. Also their latest progress and the application fields have been indicated. As a conclusion, it is believed that the research on DTC strategy with multilevel inverters will continue to develop in line with the continuous search for a high performance motion-sensorless AC drives for induction machines.

REFRENCES:

[1] A. M. Trzynadlowski, *Control of Induction Motors*: Academic Press, 2001.

[2] P. Vas, *Vector Control of AC Machines*: Oxford University Press, New York, 1990.

[3] B. K. Bose, *Power Electronics and AC Drives*: Prentice-Hall, 1986.

[4] F. Blaschke, "The principle of field orientation as applied to the new transvektor closed-loop control system for rotating-field machines," *Adjustable Speed AC Drive Systems*, 1972.

[5] K. Hasse, "Zum dynamischen Verhalten der Asynchronmaschine bei Betrieb mit variabler Standerfrequenz und Standerspannung, ("On the dynamic behavior of induction machines driven by variable frequency and variable voltage sources")," *ETZ-A, Bd*, vol. 89, pp. 77-81, 1968.

[6] X. Xu and D. W. Novotny, "Implementation of direct stator flux orientation control on a versatile DSP based system," *IEEE Transactions on Industry Applications*, vol. 27, pp. 694-700, 1991.

[7] T. G. Habetler, F. Profumo, G. Griva, M. Pastorelli, and A. Bettini, "Stator resistance tuning in a stator-flux field-oriented drive using an instantaneous hybrid flux estimator," *IEEE TRANS POWER ELECTRON*, vol. 13, pp. 125-133, 1998.

[8] I. Takahashi and T. Noguchi, "A new quick-response and high-efficiency control strategy of an induction motor," *IEEE Transactions on Industry Applications*, pp. 820-827, 1986.

[9] M. Depenbrock, "Direct self-control(DSC) of inverter-fed induction machine," *IEEE Transactions on Power Electronics*, vol. 3, pp. 420-429, 1988.

[10] J. Rodriguez, J. S. Lai, and F. Z. Peng, "Multilevel inverters: a survey of topologies, controls, and applications," *IEEE Transactions on Industrial Electronics*, vol. 49, pp. 724-738, 2002.

[11] Z. Tan, Y. Li, and M. Li, "A direct torque control of induction motor based on three-level NPCinverter," 2001.

[12] R. Zaimeddine, L. Refoufi, and E. M. Berkouk, "An Improved Direct Torque Control Strategy for Induction Motor Drive," *International Journal of Electrical and Power Engineering, Medwell Journals*, vol. 1, pp. 21 - 27, 2007.

[13] M. F. Escalante, J. C. Vannier, and A. Arzande, "Flying capacitor multilevel inverters and DTC motor drive applications," *IEEE Transactions on Industrial Electronics*, vol. 49, pp. 809-815, 2002.

[14] J. Rodr guez, J. Pontt, C. Silva, S. Kouro, and H. Miranda, "A novel direct torque control scheme for induction machines with space vector modulation," 2004.

[15] T. G. Habetler, F. Profumo, M. Pastorelli, and L. M. Tolbert, "Direct torque control of induction machines using space vector modulation," *IEEE Transactions on Industry Applications*, vol. 28, pp. 1045-1053, 1992.

[16] Y. Wang, H. Li, and X. Shi, "Direct Torque Control with Space Vector Modulation for Induction Motors Fed by Cascaded Multilevel Inverters," 2006, pp. 1575-1579.

[17] X. del Toro Garcia, A. Arias, M. G. Jayne, P. A. Witting, V. M. Sala, and J. L. Romeral, "New DTC Control Scheme for Induction Motors fed with a Three-level Inverter," *AUTOMATIKA-ZAGREB-*, vol. 46, p. 73, 2005.

[18] S. Kouro, R. Bernal, H. Miranda, C. A. Silva, and J. Rodriguez, "High-performance torque and flux control for multilevel inverter fed induction motors," *IEEE Transactions on Power Electronics*, vol. 22, pp. 2116-2123, 2007.

[19] R. Kennel and A. Linder, "Predictive control of inverter supplied electrical drives," 2000.

[20] C. A. Martins, X. Roboam, A. M. Thierry, and A. S. Carvalho, "Switching frequency imposition and ripple reduction in DTC drives by using a multilevel converter," *IEEE Transactions on Power Electronics*, vol. 12, pp. 286 -297, 2002.

[21] J. Rodríguez, J. Pontt, S. Kouro, and P. Correa, "Direct torque control with imposed switching frequency in an 11-level cascaded inverter,"

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

IEEE Transactions on Industrial Electronics, vol. 51, pp. 827-833, 2004.

[22] F. Khoucha, S. M. Lagoun, K. Marouani, A. Kheloui, and M. E. H. Benbouzid, "Hybrid cascaded H-bridge multilevel inverter motor drive DTC control for Electric Vehicles," 2009, pp. 1-6.

[23] P. Correa, M. Pacas, and J. Rodriguez, "Predictive torque control for inverter-fed induction machines," *IEEE Transactions on Industrial Electronics,* vol. 54, pp. 1073-1079, 2007.

[24] R. Ortega, N. Barabanov, G. Escobar, and E. Valderrama, "Direct torque control of induction motors: stability analysis andperformance improvement," *IEEE transactions on automatic control,* vol. 46, pp. 1209-1222, 2001.

[25] M. A. M. Prats, G. Escobar, E. Galvan, J. M. Carrasco, and R. Portillo, "A switching control strategy based on output regulation subspaces for the control of induction motors using a three-level inverter," *IEEE Power Electronics Letters,* vol. 1, pp. 29-32, 2003.

[26] S. Kouro, R. Bernal, H. Miranda, J. Rodriguez, and J. Pontt, "Direct Torque Control With Reduced Switching Losses for Asymmetric Multilevel Inverter Fed Induction Motor Drives," 2006.

[27] M. Bendyk, M. Hartman, and M. Jayne, "Investigation of direct torque control system fed by modified cascade of multilevel voltage source inverter," *IEEE Compatibility in Power Electronics, 2005,* pp. 265-272, 2005.

[28] R. Toufouti, S. Meziane, and H. Benalla, "Direct Torque Control for Induction Motor Using Intelligent Techniques," *Journal of Theoretical and Applied Information Technology,* 2007.

[29] L. Youb, A. Craciunescu, and G. Ciumbulea, "A new fuzzy logic direct torque control scheme of induction motor for electrical vehicles application," in *XIX International Conference on Electrical Machines (ICEM), 2010* Rome, 2010, pp. 1-6.

[30] X. del Toro, S. Calls, M. G. Jayne, P. A. Witting, A. Arias, and J. L. Romeral, "Direct torque control of an induction motor using a three-level inverter and fuzzy logic," in *Industrial Electronics, 2004 IEEE International Symposium on*, 2004, pp. 923-927 vol. 2.

[31] Y. Zhang, J. Zhu, Z. Zhao, W. Xu, and D. G. Dorrell, "An Improved Direct Torque Control for Three-Level Inverter-Fed Induction Motor Sensorless Drive," *Power Electronics, IEEE Transactions on,* p. 1, 2010.