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Three Level DTC_SVM for Dual Star Induction Motor Fed by Tow Cascade VSI with DPCVF_SVM Rectifier

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Abstract

We present in this paper a novel DTC-SVM scheme for a Dual Star Induction Motor fed by two 3 levels inverter with NPC structure, this type of inverter has many points of interest in comparison with the conventional 2 levels inverter, such as: sinus waveforms of the output voltage, low THD of voltage and current and low switching frequency. Also, we present in this article an improved direct power control with virtual flux (DPCVF-SVM) for the control of three phase rectifier. It is shown that the DPC-SVM presents several advantages: constant switching frequency, good dynamic response, sinusoidal line currents . . . etc.

Keywords: DSIM, VSI, DTC, DPC, SVM

Introduction

In high power variable speed AC machine drives, the performance and robustness are required, and in many applications, such as ship propulsion and locomotive traction require a great reliability [1]. One typical solution to improve the reliability, the performance and the robustness is to multiply the machine phases and to find suitable control strategies [2]; [3]. Other interesting points of the dual three phase induction motors in comparison with the classical three phases motors are: the total power will be segmented on many inverter legs, the transistor current decreases proportionally with the number of phase, low torque ripple at high frequency, reducing the THD of rotor currents [4]; [5]; [6].

A typical type of multiphase motors is the double stator induction motor (DSIM), is known as the six phase induction motor, these types of motors have been utilized in several applications (compressors, pumps, cement mills . . . [7]).

The direct torque control (DTC) scheme was proposed in 1980 by I. Takahashi [8], this strategy is one of the advanced control techniques for AC motor, it presents a high performance torque and flux control.

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The principal idea of this control strategy is based on the difference between the reference values and the estimated values of electromagnetic torque and flux, the inverter states are directly controlled for the purpose of reducing the torque and flux errors inside the band limits [9]; [10]. Conventional DTC has many drawbacks, the main is variable switching frequency and high torque ripples. Recently, from the standard DTC schemes, novel control strategy called Direct Torque Control_Space Vector Modulation (DTC-SVM) has been developed. In this novel strategy, drawbacks of the conventional DTC are eliminated. Basically, the DTC-SVM controls are the methods, which work with constant switching frequency [11].

AC/DC converters are commonly used in industrial AC drives. Several control methods have been developed for these converters. The basic control methods can be divided as follow: Voltage Oriented Control, Direct Power Control and Direct Power Control with Space Vector Modulation (DPC-SVM) [12].

VOC is the most popular control strategy. It presents high dynamic and static performance via internal current control loops [12]. Another control strategy adopted from induction motor controls is DPC. Any coordinate transformations has been used by this control strategy, instantaneous active and reactive powers has been operates directly. High dynamic is assured by hysteresis controllers and switching table. But, variable switching frequency and high sampling frequency are the main drawbacks of the look-up table based DPC method [12]; [13].

Therefore, to overcome that disadvantages, a Space Vector Modulator (SVM) was introduced to DPC structure, giving new method called Direct Power Control with Space Vector Modulator. DPC-SVM joins important advantages of SVM (constant switching frequency, unipolar voltage switching and low current distortions) with DPC features (simple and robust structure, lack of internal current control loops, good dynamics, etc.) [14]. The simulation results using Matlab/Simulink prove the efficiency and robustness of the elaborate scheme.

DSIM Modeling

The schema of stator and rotor windings for a DSIM is presented by figure 1. The 6 phases of stator are divided into 2 three phases group named: A_{s1}, B_{s1}, C_{s1} and A_{s2}, B_{s2}, C_{s2} where magnetic axes are offset by an angle α=30°. The windings of both three phase group are uniformly distributed and their axes are offset 120° apart. The three phase windings of rotor: A_r, B_r and C_r are sinusoidally distributed and their axes are offset apart by 120° [15]; [16].

Considering the following simplifying assumptions [11]; [17]:

1. The distribution of motor windings is sinusoidal;
2. The two stators have identical parameters;
3. Symmetrical construction machine;
4. The mutual leakage inductances, core losses and magnetic saturation are insignificant.

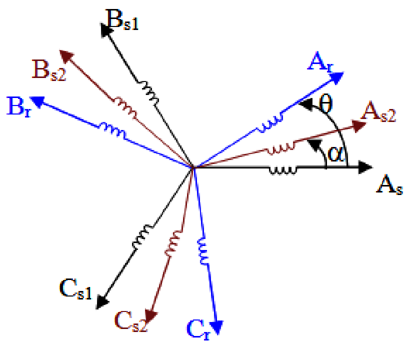

Figure 1: Windings of the Dual Star Induction Motor

The motor voltage equations are as follow [18]; [19]:

$$[V_{s1}] = \begin{bmatrix} V_{sa1} \\ V_{sb1} \\ V_{sc1} \end{bmatrix} = [R_{s1}]\,[I_{s1}] + \frac{d}{dt}\,[\Phi_{s1}]$$

$$[V_{s2}] = \begin{bmatrix} V_{sa2} \\ V_{sb2} \\ V_{sc2} \end{bmatrix} = [R_{s1}]\,[I_{s2}] + \frac{d}{dt}\,[\Phi_{s2}]$$

$$[0] = \begin{bmatrix} V_{ra} \\ V_{rb} \\ V_{rc} \end{bmatrix} = [R_r]\,[I_r] + \frac{d}{dt}\,[\Phi_r]$$

Where:

$R_{sa1} = R_{sb1} = R_{sc1} = R_{s1}$: Resistance of the first star.

$R_{sa2} = R_{sb2} = R_{sc2} = R_{s2}$: Resistance of the second star.

$R_{ra} = R_{rb} = R_{rc} = R_r$: Resistance of the rotor.

$$[I_{s1}] = \begin{bmatrix} I_{sa1} \\ I_{sb1} \\ I_{sc1} \end{bmatrix}; [I_{s2}] = \begin{bmatrix} I_{sa2} \\ I_{sb2} \\ I_{sc2} \end{bmatrix}; [I_r] = \begin{bmatrix} I_{ra} \\ I_{rb} \\ I_{rc} \end{bmatrix}$$

$$[\O_{s1}] = \begin{bmatrix} \O_{sa1} \\ \O_{sb1} \\ \O_{sc1} \end{bmatrix}; [\O_{s2}] = \begin{bmatrix} \O_{sa2} \\ \O_{sb2} \\ \O_{sc2} \end{bmatrix};$$

$$[\O_r] = \begin{bmatrix} \O_{ra} \\ \O_{rb} \\ \O_{rc} \end{bmatrix}$$

The flux expression of stator and rotor are [19]:

$$\begin{bmatrix} [\O s1] \\ [\O s1] \\ [\O s1] \end{bmatrix} = \begin{bmatrix} [Ls1s1][Ls1s2][Ls1r] \\ [Ls2s1][Ls2s2][Ls2r] \\ [Lrs1][Lrs2][Lrr] \end{bmatrix} \cdot \begin{bmatrix} [Is1] \\ [Is2] \\ [Ir] \end{bmatrix}$$

Where:

$[L_{s1s1}]$: The first star inductance matrix.

$[L_{s2s2}]$: The second star inductance matrix.

$[L_{rr}]$: The rotor inductance matrix.

$[L_{s1s2}]$: Mutual inductance matrix of stator 1 and 2.

$[L_{s2s1}]$: Mutual inductance matrix of stator 2 and 1.

$[L_{s1r}]$: Mutual inductance matrix of stator 1 and rotor.

$[L_{s2r}]$: Mutual inductance matrix of stator 2 and rotor.

$[L_{rs1}]$: Mutual inductance matrix of rotor and stator 1.

$[L_{rs2}]$: Mutual inductance matrix of rotor and stator 2.

The electromagnetic torque expression is given by [7]; [20]; [18]:

$$Tem = \left(\tfrac{P}{2}\right)\left([Is1]\tfrac{d}{d\theta}[Ls1r][Ir] + [Is2]\tfrac{d}{d\theta}[Ls2r][Ir]\right)$$

The following equations define the Park machine model using the rotating field (d, q) reference frame [15].

The machine model in the Park frame is shown in figure 2.

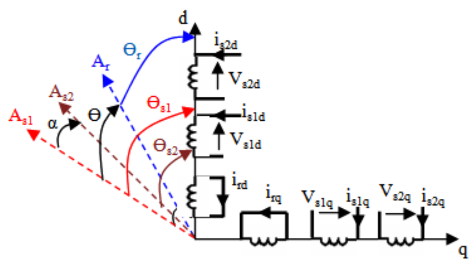

Figure 2: Representation of DSIM in the Park frame

$$\begin{cases} cVs1d = Rs1.Is1d + \frac{d}{dt}.\Phi s1d - ws.\Phi s1q \\ Vs1q = Rs1.Is1q + \frac{d}{dt}.\Phi s1q + ws.\Phi s1d \\ Vs2d = Rs2.Is2d + \frac{d}{dt}.\Phi s2d - ws.\Phi s2q \\ Vs2q = Rs2.Is2q + \frac{d}{dt}.\Phi s2q + ws.\Phi s2d \\ 0 = Rr.Ird + \frac{d}{dt}.\Phi rd - wsr.\Phi rq \\ 0 = Rr.Irq + \frac{d}{dt}.\Phi rq + wsr.\Phi rd \end{cases}$$

$$\begin{cases} \Phi s1d = Ls1.Is1d + Lm(Is1d + Is2d + Ird) \\ \Phi s1q = Ls1.Is1q + Lm(Is1q + Is2q + Irq) \\ \Phi s2d = Ls2.Is2d + Lm(Is1d + Is2d + Ird) \\ \Phi s2q = Ls2.Is2q + Lm(Is1q + Is2q + Irq) \\ \Phi rd = Lr.Ird + Lm(Is1d + Is2d + Ird) \\ \Phi rq = Lr.Irq + Lm(Is1q + Is2q + Irq) \end{cases}$$

Where:

L_m: Cyclic mutual inductance of first star, second star and rotor.

The mechanical equation is given by:

$$J.\frac{d\omega}{dt} = Tem - Tr - Fr.\omega$$

$$Tem = p\frac{Lm}{Lr+Lm}\left(\phi rd\left(Is1q + Is2q\right) - \phi rq\left(Is1d + Is2d\right)\right)$$

The three level NPC inverter

The standard inverter generally utilized in electrical machine drive is the two-level VSI, which has several disadvantages (DC bus voltage limited, high voltage and current THD,...). For obtained good performances and limited these restrictions, the three levels NPC voltage source inverter is used [21].

The 3 level neutral point clamped inverter presented in figure 3, is considered one of the most used multilevel inverter. This type of VSI has a few points of interest over the standard two-level inverter, for example, almost sinusoidal voltage waveforms, low THD and switching frequency. The voltage imbalance produced in the capacitors of the DC-link when one of the phases is connected to the middle or to the neutral point, constitute the principle disadvantage of this type of inverter [22].

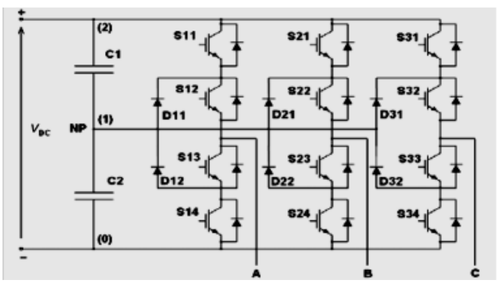

Figure 3: Three-level NPC VSI

In figure 4, the different vectors or VSI states available in a three-level VSI are presented. As it can be seen, there are 4 different kinds of vectors depending on the module:

- Zero vectors: V_z (with 3 possible configurations).
- Large vectors: V_{1l}, V_{2l}, V_{3l}, V_{4l}, V_{5l}, V_{6l}.
- Medium vectors: V_{1m}, V_{2m}, V_{3m}, V_{4m}, V_{5m}, V_{6m}.
- Small vectors: V_{1s}, V_{2s}, V_{3s}, V_{4s}, V_{5s}, V_{6s}. (with 2 possible configurations for each).

The state of the switches for each leg (CA, CB and CC) is shown in brackets (2: phase connected to the positive of the DC-link; 1: phase connected to the middle point of the DC-link (NP); 0: phase connected to the negative of the DC-link).

Direct torque control

The direct torque and flux control strategy permits to control directly and independently the flux and the electromagnetic torque, by the selection of appropriate switching vector [23]. The figure 5 presents the classical DTC method for a DSIM. The flux reference value ($\varnothing_s{}^*$) and the torque reference value ($T_{em}{}^*$) are compared to their real values, the obtained errors are respectively; the inputs of a two level hysteresis regulator of the flux, and three level hysteresis regulator of the torque, for the purpose of controlling the motor in the rotation negative direction.

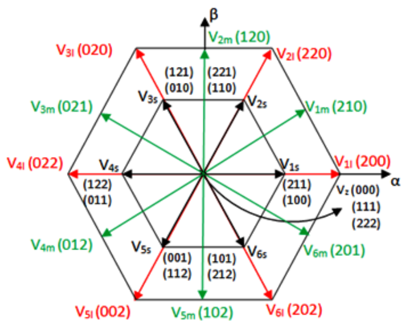

Figure 4: Diagram of voltage space vectors for a Three-level NPC VSI

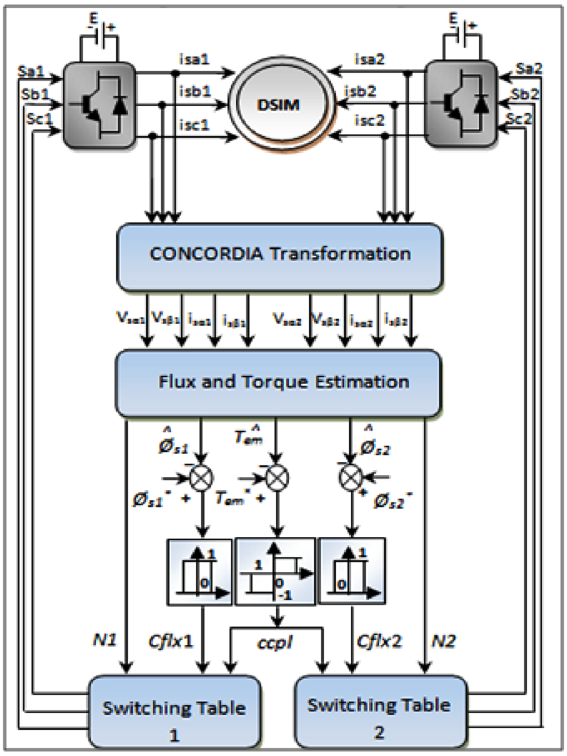

Figure 5: Schematic diagram of the conventional DTC strategy for DSIM

Direct torque control based on space vector modulation

Principal drawbacks of classical DTC are high ripple of torque and variable switching frequency. Several methods have been used to minimize the torque ripple and improve the conventional DTC performance. The common technique of them is based on Space Vector Modulation (DTC_SVM) [24]. SVM strategies have many points of interest such as: better exploitation of DC current, torque ripple minimization, minimization of the THD alternating current, considerable decrease in switching losses, and simplicity of implementation in the programmable systems. At each cycle period, a preview technique is used to obtain the voltage space vector required to exactly compensate the flux and torque errors. The torque ripple for this proposed method is considerably improved and we obtained a constant switching frequency [24]; [25]. The proposed scheme is presented in figure 6.

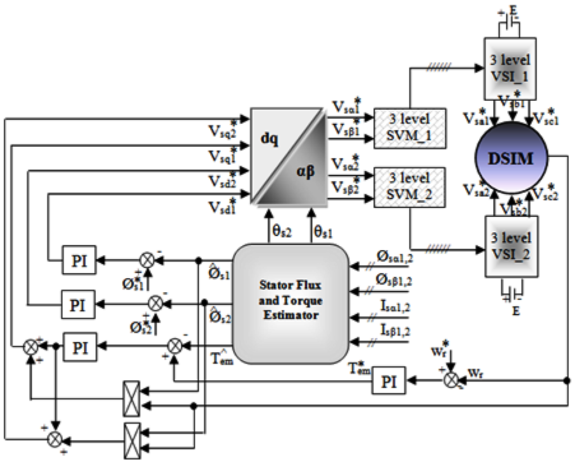

Figure 6: Three Level DTC-SVM of DSIM

Direct power control with virtual flux

The fundamental idea of Direct Power Control for converters is similar to the Direct Torque Control (DTC) for induction motors. Instead of electromagnetic torque and flux, we control the instantaneous active (p) and reactive (q) powers. In this section we interested to the direct power control based on virtual flux (DPC-VF). This control strategy which is used to replace that based on the voltage estimation makes it possible to decrease the THD while keeping the control advantage without line voltage sensor.

The figure 7 shows the block scheme of DPC based on virtual flux.

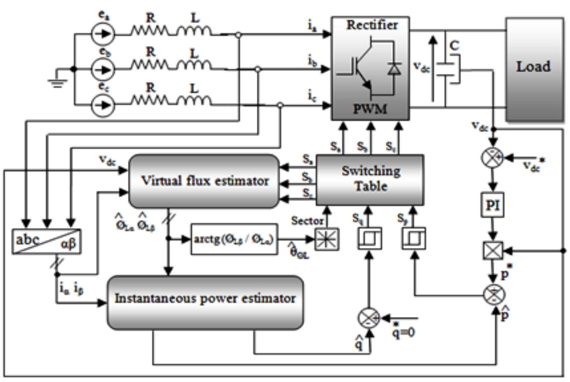

Figure 7: Block scheme of DPC_VF

DPC with virtual flux based on space vector modulation

The most disadvantages of the DPC using hysteresis controllers are sampling and variable switching frequency. These drawbacks can be eliminated by inserting the SVM block in place of the switching table. Otherwise, we can replace the sensors of line voltage by virtual flux estimator, which will offer several advantages to the system, such as: reliability, galvanic isolation and cost reduction. In the Virtual Flux based Direct Power Control Space Vector Modulation scheme, hysteresis comparators are replaced by conventional PI controllers [26]. The principal of the proposed scheme as presented in figure 8.

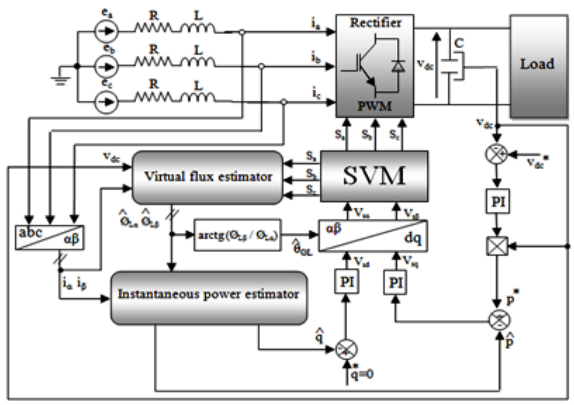

Figure 8: Block scheme of DPCVF_SVM

Results and discussion

The figure 9 and the figure 10 shows that the magnitude of stator flux oscillation, the electromagnetic torque ripples and the perturbation reject of speed are minimized in three-level DTC-SVM method as compared with a conventional DTC. The current waveform obtained is sinusoidal in both schemes. The figure 11 and the figure 13 show the performance of the DPC and DPC-SVM based on virtual flux. As could be seen in these figures that DC bus voltage, active and reactive powers reach their references values with very low ripple in DPC-VF-SVM. The line current is controlled to be sinusoidal wave; it is forced to follow in phase with the corresponding voltage which indicates the unity power factor. We remark that the Total Harmonic Distortion (THD) of the line current is decreasedDPC-SVM (figure. 12 and figure. 14). The figure 15 shows the dynamic responses of DSIM, the proposed scheme keeps its robustness and performances under load and speed variation.

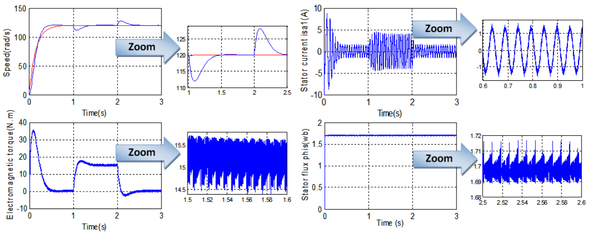

Figure 9: Dynamic responses of DSIM with a conventional DTC scheme

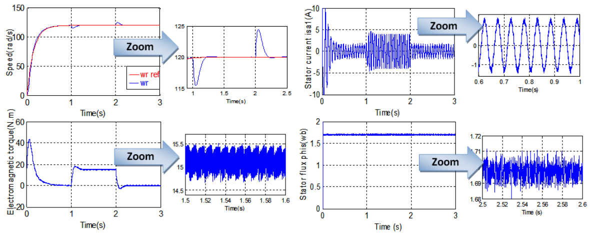

Figure 10: Dynamic responses of DSIM with a three-level DTC-SVM scheme

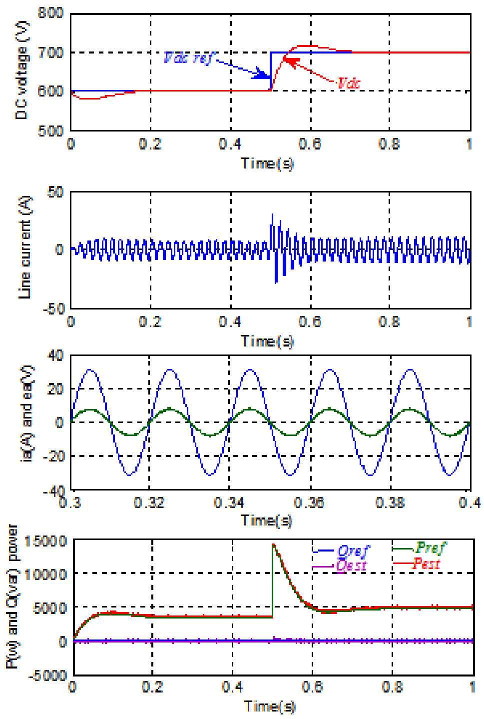

Figure 11: Input and output waveforms of the DPC-VF rectifier

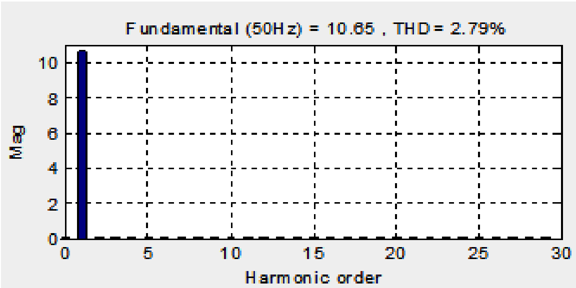

Figure 12: Line current harmonics spectrum

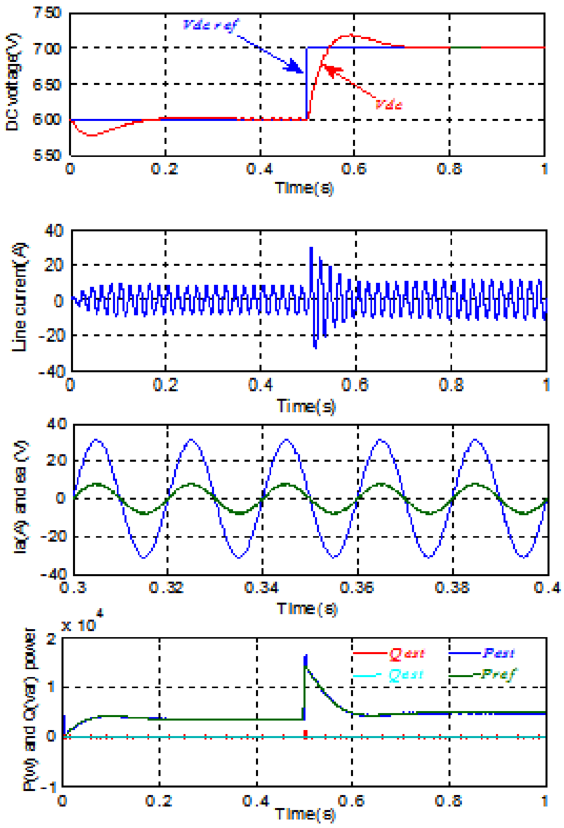

Figure 13: Input and output waveforms of the DPC-VF-SVM rectifier

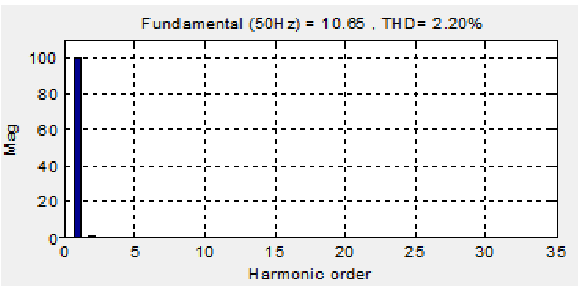

Figure 14: Line current harmonics spectrum

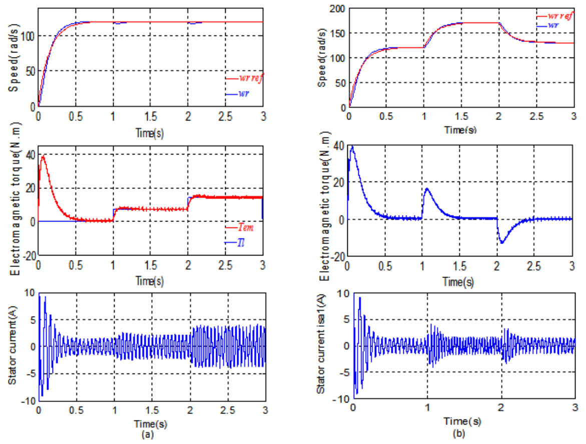

Figure 15: Dynamic responses of DSIM using 3 level DTC-SVM and DPC-VF-SVM: (a) with load torque variation (b) with speed variation

Conclusion

We are proposed in this paper a novel control scheme with multilevel DTC-SVM and DPC-SVM based on virtual flux of a Dual Star Induction Motor. The features of the proposed method can be summarized as follows: good dynamic of electromagnetic torque and flux, fixed switching frequency, low flux and torque ripple, sinusoidal stator currents waveform, a unit power factor and low THD.

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