DTC of Induction Motor using Cascaded H-Bridge Multilevel Inverter

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***Abstract*- As earlier studies have pointed out the limitations of conventional inverters, especially in high-voltage and high-power applications. In recent years, multilevel inverters are becoming increasingly popular for high-power applications due to their improved harmonic profile and increased power ratings. Several studies have been reported in the literature on multilevel inverters topologies, control techniques, and applications. However, there are few studies that actually discuss or evaluate the performance of induction motor drives associated with three-phase multilevel inverter. This paper presents direct torque control (DTC) of induction motor using cascaded H-Bridge multilevel inverter. In this case, symmetrical arrangements of five- and seven-level H-bridge inverters are compared in order to find an optimum arrangement with lower switching losses and optimized output voltage quality. The carried out simulations show that an asymmetrical configuration provides nearly sinusoidal voltages with very low distortion, using less switching devices. Moreover, torque ripples are greatly reduced.**

***Keywords*-Direct Torque Control (DTC), Induction motors, Multilevel inverters.**

I. INTRODUCTION

Multilevel voltage-source inverters are intensively studied for high-power applications [1-5], and standard drives for medium-voltage industrial applications have become available [6], [7]. Solutions with a higher number of output voltage levels have the capability to synthesize waveforms with a better harmonic spectrum and to limit the motor winding insulation stress. However, their increasing number of devices tends to reduce the power converter overall reliability and efficiency.

On the other hand, solutions with a low number of levels either need a rather large and expensive *LC* output filter to limit the motor winding insulation stress, or can only be used with motors that do withstand such stress.

The induction motor seems to be a very interesting solution for EV's propulsion. FOC and DTC have emerged as the standard industrial solutions to achieve high dynamic performance [8-10]. However some drawbacks of both methods have motivated important research efforts in the last decades. Particularly for DTC, the high torque ripple and the variable switching frequency introduced by the hysteresis comparators have been extensively addressed [11-12]. In addition, several contributions that combine DTC principles together with PWM and SVM have been reported to correct these problems. This approach is based on the load angle control, from which a voltage reference vector is computed which is finally modulated by the inverter [13]. Although one major feature of classic DTC is the absence of modulators and linear controllers, this approach has shown significant improvements and achieves similar dynamic performance. On the other hand, power converter technology is continuously developing, and cascaded multilevel inverters have become a very attractive solution for EV applications, due to its modular structure, higher voltage capability, reduced common mode voltages, near sinusoidal outputs, and smaller or even no output filter [14-17].

In general, cascaded multilevel inverter may be classified in two groups. The first one refers to the amplitude of isolated DC sources devoted to supply each H-bridge cell. If the amplitude of all sources is equal, then the inverter is called symmetrical, otherwise, if at least one of the sources present different amplitude, then it will be called asymmetrical. The second classification label the multilevel inverter whether hybrid or not. If the converter is implemented with different semiconductor device technologies, different nature of DC sources (fuel cells,batteries and supercapacitors) and/or if it presents a hybridmodulation strategy, then it is classified as hybrid [18-20]. This structure greatly simplifies the converter complexity. The proposed control algorithm eliminates the need of additional isolated DC sources. The control strategy regulates the DC link voltages of capacitors connected to the smallest voltages of a two cells 7-level cascaded H-bridge inverter [21]. Specifically and in comparison to previous works [22- 23], the proposed control do not use an angle for capacitor voltage regulation but a comparison voltage level.

Many studies have been conducted toward improving multilevel inverter. Some studies dealt with innovative topologies, such as cascaded multilevel inverter, to optimize the components utilization and the asymmetrical multilevel inverter to improve the output voltage resolution. Other studies focused on developing advanced control strategies or upgrading the voltage source inverter strategies for implementation in multilevel inverter.

In symmetrical multilevel inverter, all H-bridge cells are fed by equal voltages, and hence all the arm cells produce similar output voltage steps. However, if all the cells are not fed by equal voltages, the inverter becomes an asymmetrical one. In this inverter, the arm cells have different effect on the output voltage. Other topologies are possible, such as the neutral point clamped fed by unequal capacitors.

Asymmetrical multilevel inverter has been recently investigated. In all these studies, H-bridge topology has been considered and a variety of selection of cascaded cell numbers and dc-sources ratios has been adopted. The suggested pulse width-modulation strategy that maintains the high-voltage stage to operate at low frequency limits the source-voltage selection.

One of the methods that have been used by a major multilevel inverter manufacturer is direct torque control (DTC), which is recognized today as a high-performance control strategy for ac drives. Several authors have addressed the problem of improving the behavior of DTC ac motors, especially by reducing the torque ripple. Different approaches have been proposed. Although these approaches are well suitable for the classical two-levels inverter, their extension to a greater number of levels is not easy.

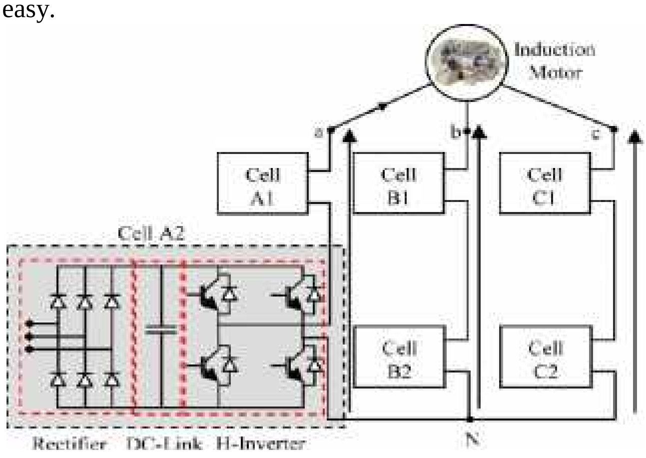


Fig.1: Structure of two cells cascaded multilevel inverter

II. CASCADED H-BRIDGES STRUCTURE

The cascaded H-bridge inverter consists of power conversion cells, each supplied by an isolated dc source on the dc side, which can be obtained from batteries, fuel cells, or ultracapacitors, and series-connected on the ac side. The advantage of this topology is that the modulation, control, and protection requirements of each bridge are modular. It should be pointed out that, unlike the diode-clamped and flying-capacitor topologies, isolated dc sources are required for each cell in each phase. Fig.1 shows a three-phase topology of a cascade inverter with isolated dc-voltage sources. An output phase-voltage waveform is obtained by summing the bridges output voltages

$$V_o(t) = V_{o,1}(t) + V_{o,2}(t) + \ldots\ldots\ldots\ldots + V_{o,N}(t)$$

Where$N$ is the number of cascaded bridges

If all dc-voltage sources in Fig.1 are equal to V_{dc}, the inverter is then known as a symmetric multilevel one. The effective number of output voltage levels n in symmetric multilevel inverter is related to the cells number by

$$n = 1+2N$$

The Max.output voltage is given by $V_{o,Max} = N\ V_{DC}$

To provide a large number of output levels without increasing the number of inverters, asymmetric multilevel inverters can be used.

In and, it is proposed to chose the dc voltages sources according to a geometric progression with a factor of 2 or 3. For N of such cascade inverters, one can achieve the following distinct voltage levels.

$$n = 2^{N+1}-1, \text{ if } V_{dc,j} = 2^{j-1}V_{dc}, \quad j=1,2,\ldots\ldots.N$$
$$n = 3^{N}, \quad \text{ if } V_{dc,j} = 3^{j-1}V_{dc}, \quad j=1,2,\ldots\ldots.N$$

For example, Figs. 3 and 4 illustrated typical waveforms of Fig. 1 multilevel inverter with, respectively, two dc sources (V_{dc}) and($2V_{dc}$) (seven-levels output) and two dc sources (V_{dc})and($3V_{dc}$) (nine-levels output).

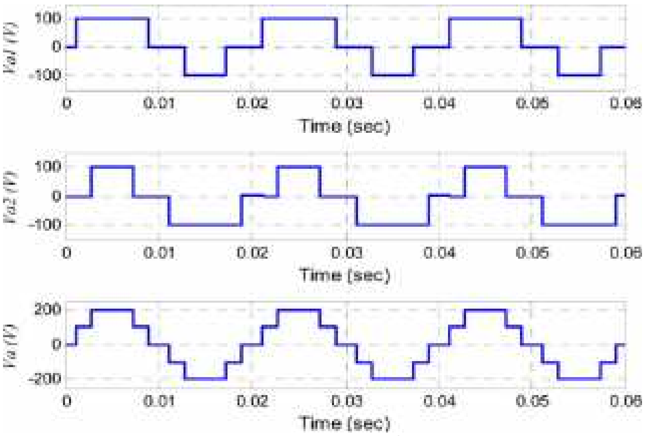


Fig. 2: Symmetric multilevel inverter with five-levels output voltage synthesis

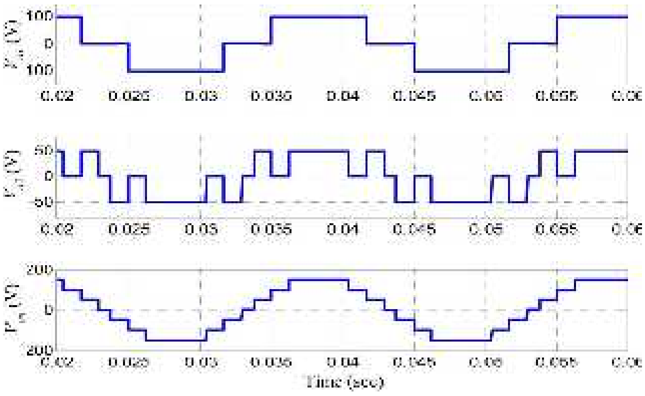


Fig. 3: Asymmetric multilevel inverter with seven-levels output voltage synthesis.

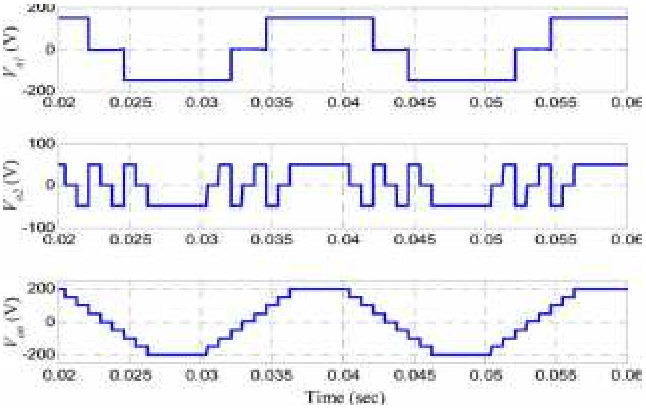


Fig. 4: Asymmetric multilevel inverter with nine-levels output voltage synthesis.

The maximum output voltage of these *N* cascaded multilevel inverters is

$$V_{o,\,Max} = (2^N-1)\, V_{dc} \text{if} V_{dc,j} = 2^{j-1} V_{dc}\ , \qquad j=1,2,\ldots\ldots N$$

$$V_{o,\,Max} = [(3^N-1)/2]\, V_{dc} \text{if} V_{dc,j} = 3^{j-1} V_{dc}\ , \quad j=1,2,\ldots\ldots N$$

TABLE ICOMPARISON OF MULTILEVEL INVERTERS

	Symmetrical inverter	Asymmetrical inverter	
		Binary	Ternary
N	$2N+1$	$2^{N+1}-1$	3^N
DC sources number	N	N	N
Switches number	$4N$	$4N$	$4N$
$V_{o,MAX}$ [pu]	N	2^N-1	$(3^N-1)/2$

III. INDUCTION MOTOR DIRECT TORQUE CONTROL

DTC is an alternative method to flux-oriented control. However, in the standard version, important torque ripple is obtained even at high sampling frequencies. Moreover, the inverterswitching frequency is inherently variable and very dependent on torque and shaft speed. This produces torque harmonics with variable frequenciesand an acoustic noise with disturbance intensities very dependent on these mechanical variables and particularly grating at lowspeed. The additional degrees of freedom (space vectors, phase configurations, etc.) provided by the multilevel inverter should, therefore, be exploited by the controlstrategy in order to reduce these drawbacks.

The stator flux vector an induction motor is related to the stator voltage and current vectors by

$$d\phi_s(t)/dt = V_s(t) - R_s i_s(t)$$

Maintaining $V_s$constant over a sample time interval and neglecting the stator resistance, the integration yields

$$\Delta\ \phi_s(t) = \phi_s(t) - \phi_s(t-\Delta t) = \int^{t}_{t-\Delta t} V_s \Delta t$$

The above equation reveals that the stator flux vector is directly affected by variations on the stator voltage vector. On the contrary the influence of V_s over the rotor flux is filtered by the rotor and stator leakage inductance, and is, therefore, not relevant over a short-time horizon. Since the stator flux can be changed quickly while the rotor flux rotates slower, the angle between both vectors *θ*sr can be controlled directly by *vs*. a graphical representation of the stator and rotor flux dynamic behavior is illustrated in Fig. 1. The exact relationship between stator and rotor flux shows that keeping the amplitude of φsconstant will produce a constant flux *φr*.

The exact relationship between stator and rotor flux shows that keeping the amplitude of *φs*constant willproduce a constant flux *φr*

Since the electromagnetic torque developed by an induction motor can be expressed by

$$T_e = \frac{3}{2} p \frac{L_m}{\sigma L_s L_r} \emptyset_s \emptyset_r sin\theta_{sr}$$

it follows that change in *θ*sr due to the action of *v*sallows for direct and fast change in the developed torque. DTC uses this principle to achieve the induction motor desired torque response, by applying the appropriate stator voltage vector to correct the flux trajectory.

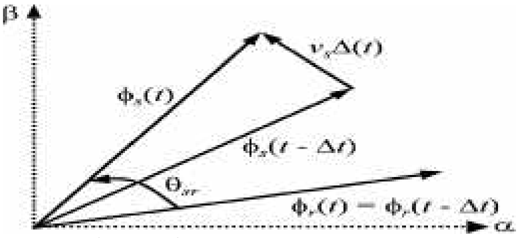


Fig. 5: Influence of *v*sover *φs*during a simple interval Δ*t*.

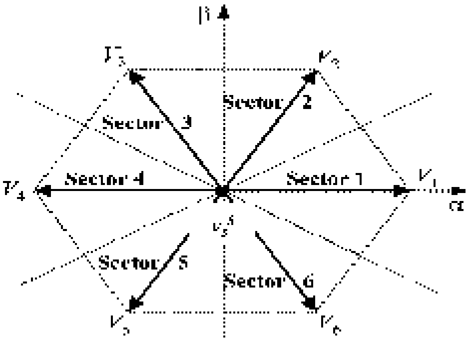


Fig.6: Possible voltage changes Δ*vk s* that can be applied from certain v_S^K

Figure 6 illustrates voltage vectors generated by the inverter at instant *t*=*k*, denoted by *vk s* (central dot). The next voltage vector, to be applied to the load *vk*+1 *s*, can be expressed by

$$V_s^{k+1} = V_s^{k} + \Delta V_s^{k}$$

WhereΔ*vks*= *{vi* |*i* = 1, . . . ,6*}*. Each vector *vi*corresponds to one corner of the elemental hexagon illustrated in gray and by the dashed line in Figure 5.4. The task is to determine which *vk*+1 *s* will correct the torque and flux responses, knowing the actual voltage vector *vk s* , the torque and flux errors *ek φ* and *ek T* , and the stator flux vector position (sector determined by angle *θs*). Note that the next voltage vector *vk*+1 *s* applied to the load will always be one of the six closest vectors to the previous *vk s* ; this will soften the actuation effort and reduce high dynamics in torque response due to possible large changes in the reference.

Table summarizes vector selections for the different sectors and comparators output (desired *φs*and *Te*corrections).

TABLE IIVOLTAGE VECTOR SELECTION LOOKUP

Sector	$\text{sign}(e_\phi^{\,k}, e_T^{\,k})$			
	(+,+)	(+,–)	(–,+)	(–,–)
1	V_2	V_6	V_3	V_5
2	V_3	V_1	V_4	V_6
3	V_4	V_2	V_5	V_1
4	V_5	V_3	V_6	V_2
5	V_6	V_4	V_1	V_3
6	V_1	V_5	V_2	V_4

To implement the DTC of the induction motor fed by a hybrid H-bridge multilevel inverter, one should determine at each sampling period, the inverter switch logic states as a function of the torque and flux instantaneous values for the selection of the space vector in the *α*–*β* frame

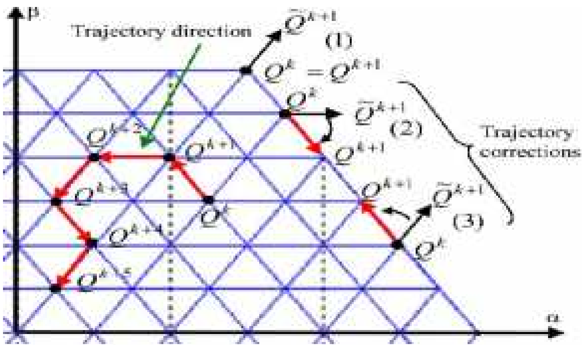
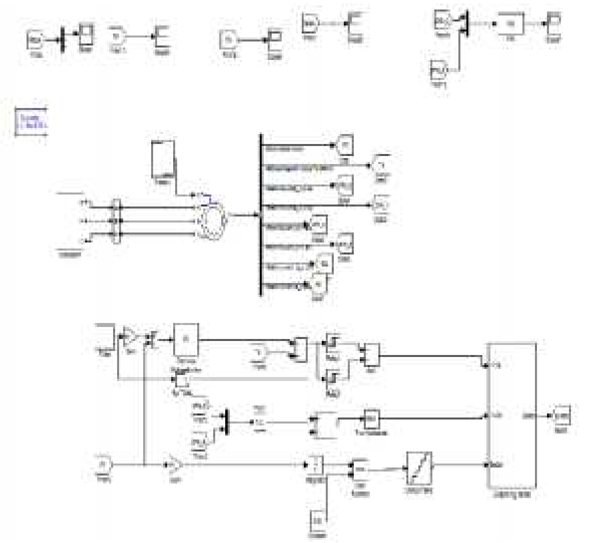


Fig. 7: Optimal space vector tracking and trajectory correction in the stationaryα–β frame.

First task: It aims at the control of the electromagnetic stateof the induction motor. The torque and flux instantaneousValues and their variations will be taken into account forthe space vector selection in the α–β. Once the space isChosen, the phase levels sequence can be selected. To ensure this task, one should detect the space vector positionin the α–β frame (Qkat sampling time k). The algorithmmust then select the next position Qk+1 to be achieved beforenext sampling instant $k + 1$ (see Fig. 8) in order to reduce voltage steps magnitude. Only one step displacement next sampling instant $k + 1$ (see Fig. 8) in order to reduce voltage steps magnitude. Only one step displacement in the α–β frame is authorized per sampling period Ts. Hence, in the absence of inverter saturation, Qk+1 must coincide with one of the six corners of the elementary hexagon centered at Qk. The same procedure will be carried out at the next period in order to determine the next trajectory direction, yielding Qk+2, which in turn will coincide with one of the six corners of the new elementary hexagon centered at Qk+1. In case of inverter saturation (if Qkgives an unreachable point for Qk+1), a trajectory correction is necessary (see Fig. 7). In cases (2) and (3), the closest displacement direction is selected. Case (1) illustrates a particular situation in which no switching should be performed, since the nearest reachable trajectory goes roughly toward the opposite sense of the favored one given by the lookup table Table II.

IV. SIMULATION RESULTS



A. Results of Five level cascaded H-Bridge inverter

Torque waveform:
Note:In this case the required torque is 10 N-m

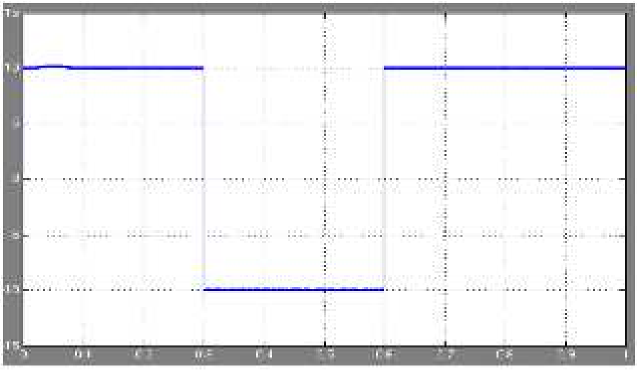


Fig 8: Five level cascaded H-Bridge inverter torque waveform

Flux Waveform:

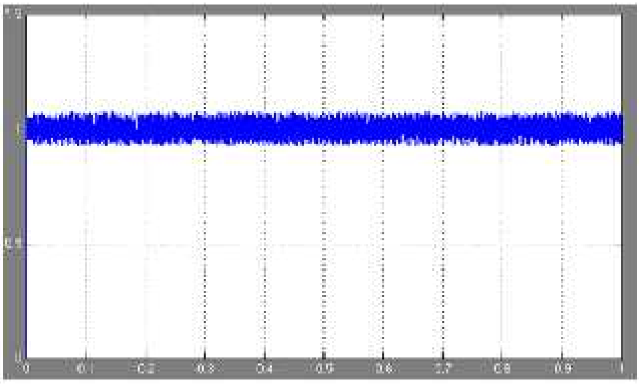


Fig 9: Five level Cascaded H- Bridge inverter flux waveform

Current Waveform:

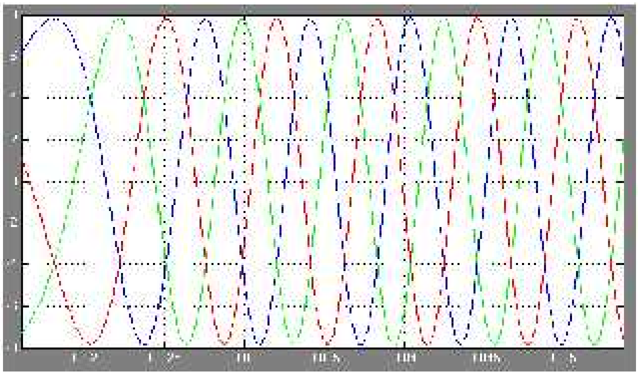


Fig 10: Five level Cascaded H-Bridge inverter current wave form

Speed Waveform:

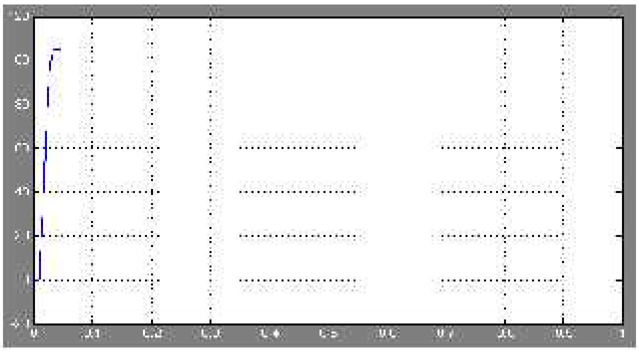


Fig 11: Five level Cascaded H-Bridge inverter speed waveform

Voltage Waveform:

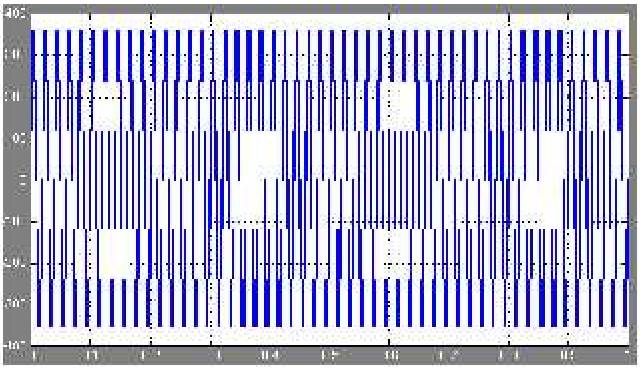


Fig 12: Five level cascaded H-Bridge inverter Voltage wavefo

B. Results of Seven level cascaded H-Bridge inverter

Torque Waveform:

Note: In this case required torque 20N-m

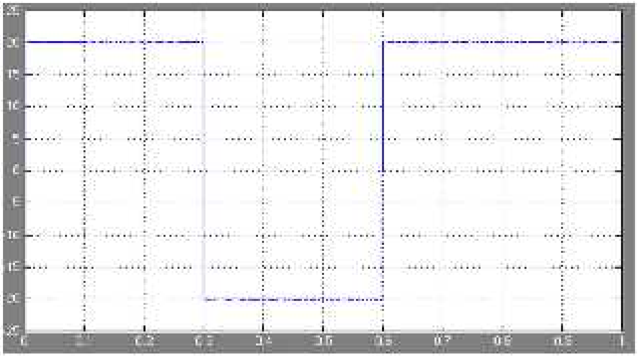


Fig 13: Seven level cascaded H-Bridge inverter Torque Wave form

Flux Waveform:

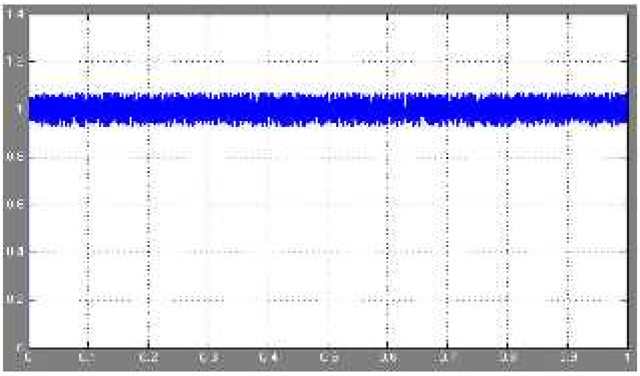


Fig 14: Seven level cascaded H-Bridge inverter Flux wave form

Current Waveform:

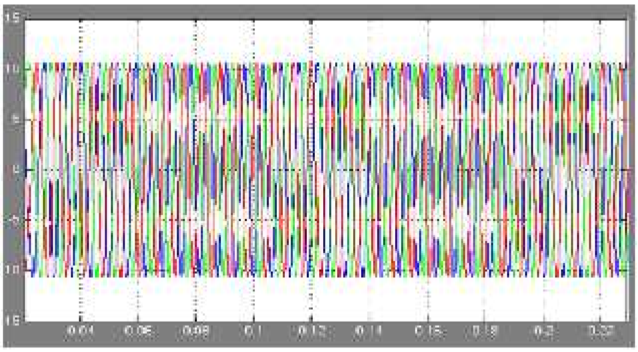


Fig 15: Seven level cascaded H-Bridge inverter Current wave form

Speed Waveform:

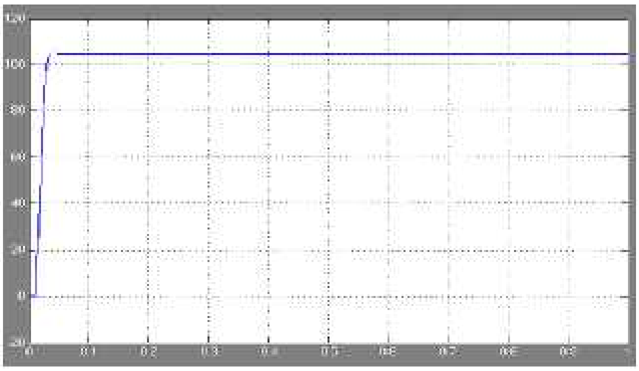


Fig 16: Seven level cascaded H-Bridge inverter Speed wave form

Voltage Waveform:

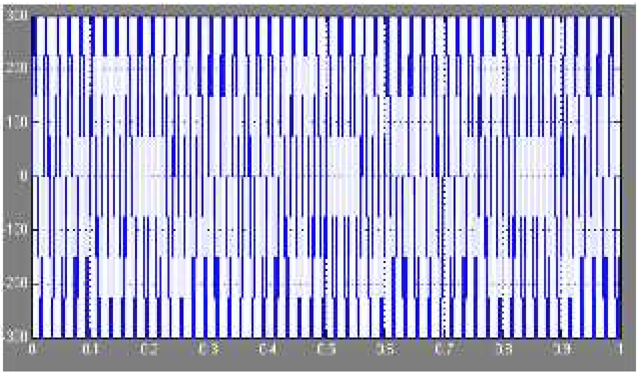


Fig 17: Seven level cascaded H-Bridge inverter Voltage wave form

Figs. 8–12 and Figs. 13–17 show simulation results for five levels cascaded and seven-levels H-bridge inverter, respectively.

The output voltages form with five level and seven-levels stepped multilevel waveform can be clearly appreciated; the motor currents complete the overview of the performance of the drive. They appear completely sinusoidal, since the low-pass nature of the load has filtered the high-frequency content of the applied voltage.The stator flux with constant amplitude imposed by the flux controller confirms the good dynamic performance of the drive. The most important results are that torque ripple has been almost eliminated in comparison to five-levels classic DTC.

V.CONCLUSION

In this paper a comparison studies for a cascaded H-bridge multilevel DTC induction motor drive. Indeed, symmetrical five- and seven-levels H bridge inverters have been compared in order to find an optimum arrangement with lower switching losses and optimized output voltage quality. The carried out simulation shows that anproposed configuration provides nearly sinusoidal voltages with very low distortion. In addition, torque ripples are greatly reduced, proposed multilevel inverter enables a DTC solution for high-power induction motor drives, not only due to the higher voltage capability provided by multilevel inverters, but mainly due to the reduced switching losses and the improved output voltage quality, which provides sinusoidal current without output filter.

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APPENDIX

TABLE IIIRATED DATA OF SIMULATED INDUCTION MOTOR

Rating	1 KW
Frequency	F = 50Hz
Voltage	V= 400 V
Speed	N= 1420 rpm
Stator resistance Ω	R_s = 4.67
Rotor resistance	R_r = 8Ω
Self inductance of stator and rotor	L_s=L_r= 0.347H
Mutual Inductance	M = 0.366H
Inertia	J = 0.06 kg.m^2

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