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A Comparison of Symmetrical and Asymmetrical Three -Phase Cascaded H-Bridge Multilevel Inverter Using Novel Control Technique for DTC Induction Motor Drives

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Abstract

There are problems in the limitations of conventional inverters, especially in high-voltage and high-power applications. Recently 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 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 a comparison study of symmetrical and asymmetrical for a cascaded H-bridge multilevel using flexible control technique and also direct torque control (DTC) for induction motor drive. In this case, symmetrical and asymmetrical arrangements of five-level, seven-level, nine-level and eleven H-bridge inverters are compared using flexible control technique vector space in order to find an optimum arrangement with lower switching losses and optimized output voltage quality. So, as to decrease the THD value (total harmonic distortion) the number of levels is increased. The experiments show that an asymmetrical configuration provides nearly sinusoidal voltages with very low distortion, using less switching devices. Moreover, torque ripples are greatly reduced by increasing number of levels we can bring step waveform to nearly sinusoidal waveform by decreasing the THD value. Thus ripples are reduced and efficiency is increased.

Index Terms- THD (Total harmonic distortion), Direct torque control (DTC), multilevel inverters, induction motor.

I. INTRODUCTION

Inverters are often used to provide power to electronics in the case of a power outage or for activities such as camping, where no power is available. An inverter converts a direct current (DC) or battery power into an alternating current (AC) or House hold power A MULTILEVEL inverter is more powerful inverter which are intensively studied for high-power applications [1],[2], and standard drives for medium-voltage industrial applications have become available[3],[4]. 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. Thus this multilevel inverter provides energy in high-power situations.

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 [5]. Other studies focused on developing advanced control strategies or upgrading the voltage source inverter strategies for implementation in multilevel inverter [6], [7].

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 behaviour of DTC ac motors, especially by reducing the torque ripple. Different approaches have been proposed. Throughout this paper, a theoretical background is used to design a strategy compatible with hybrid cascaded H-bridge multilevel inverter; symmetrical and asymmetrical configuration are implemented and compared. Experimental results obtained for an asymmetrical inverter-fed induction motor confirm the high dynamic performance of the used method, presenting good performances and very low torque ripples and efficiency is increased by reducing THD value using FET analysis. 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.

Asymmetrical multilevel inverter has been recently investigated [8], [9]. In all these studies, H-bridge topology has been considered and a variety of selection of cascaded cell numbers and dc-sources ratios have been adopted [8]. 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 [10]–[13]. 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 [14].

Throughout this paper, a theoretical background is used to design a strategy compatible with hybrid cascaded H-bridge multilevel inverter; symmetrical and asymmetrical configuration is implemented and compared [15]. Experimental results obtained for an asymmetrical inverter-fed induction motor confirm the high dynamic performance of the used method, presenting good performances and very low torque ripples.

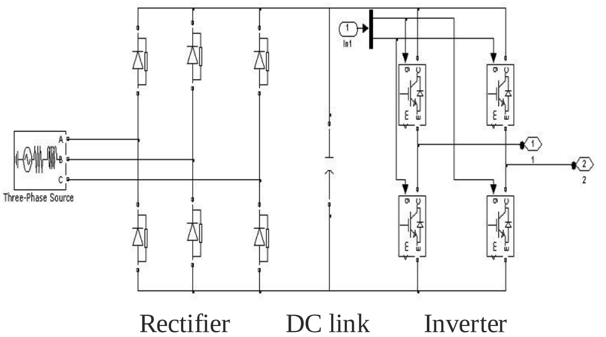

Fig. 1. Structure of cascaded multilevel inverter.

II. CASCADED H-BRIDGES STRUCTURE AND OPERATION

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 ultra capacitors [15],[17], 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. 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.

$$v_o(t) = v_{o,1}(t) + v_{o,2}(t) + \dots\dots + v_{o,N}(t) \qquad (1)$$

where N is the number of cascaded bridges.
The inverter output voltage Vo(t) may be determined from the individual cells switching states

$$Vo(t) = \sum_{j=1}^{N} (\mu_{j-1}) V_{dc,j}\,, \quad \mu_{j=0,1} \qquad \dots\dots(2)$$

If all dc-voltage sources in Fig.1 are equal to Vdc, 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

$$\mathbf{n=1+2N} \qquad (3)$$

The maximum output voltage Vo,Max is

$$Vo,Max = N\ Vdc, \qquad (4)$$

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

In [18] and [19], it is proposed to chose the dc-voltage sources according to a geometric progression with a factor of 2 or 3,for N such cascaded inverters one can achieve thefollowing distinct voltage levels

$$\left\{ \begin{array}{l} n=2^{n+1}-1, \text{ if } V_{dc,i}= 2^{j-1}V_{dc}, i= 1, 2,\dots, N \\ n=3^{N} \quad , \text{ if } V_{dc,j}= 3^{j-1}V_{dc}, j= 1, 2,\dots, N \end{array} \right. \quad (5)$$

TABLE I
COMPARISON 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. DTC INDUCTION MOTOR

DTC is an alternative method to flux-oriented control [12]. However, in the standard version, important torque ripple is obtained even at high sampling frequencies

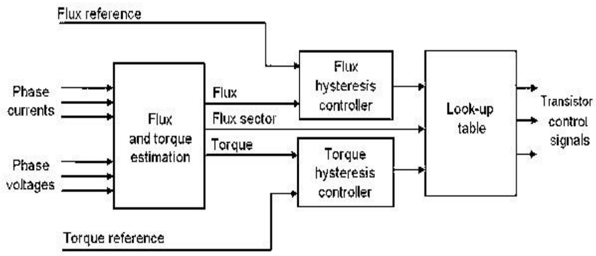

Fig2: Overview of key competing DCT control platforms

Stator flux linkage is estimated by integrating the stator voltages. Torque is estimated as a cross product of estimated stator flux linkage vector and measured motor current vector. The estimated flux magnitude and torque are then compared with their reference values. If either the estimated flux or torque deviates from the reference more than allowed tolerance, the transistors of the variable frequency drive are turned off and on in such a way that the flux and torque errors will return in their tolerant bands as fast as possible. Thus direct

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torque control is one form of the hysteresis or bang-bang control.

Moreover, the inverter switching frequency is inherently variable and very dependent on torque and shaft speed. This produces torque harmonics with variable frequencies and an acoustic noise with disturbance intensities very dependent on these mechanical variables and particularly grating at low speed. The additional degrees of freedom (space vectors, phase configurations, etc.) provided by the multilevel inverter should, therefore, be exploited by the control strategy in order to reduce these drawbacks.

Among the n^3switching states of n-level inverter, there is n zero states, where zero output voltages are produced. Among the (n^3 −n) nonzero remaining states, there are unique states and mutual states. The unique states provide voltage vectors that cannot be obtained by any other states. The mutual state on the other hand, provides a set of output voltages that can be provided by some other mutual state or states. The equivalent mutual states share the same voltage vectors. The n-level inverter has [$(n-1)^3 - (n-1)$] nonzero mutual states. The voltage vectors of the five-level inverter are shown in Fig. 4. The number of distinct voltage vectors obtained from n-level inverter is [$n^3 - (n-1)^3$]. The existence of equivalent mutual states has usually been used.

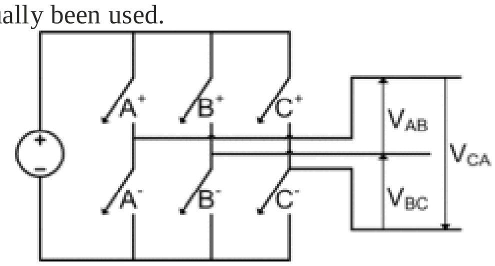

Fig3: Basic Structure

			C+	A−	B−	C−	V_{AB}	V_{BC}	V_{CA}	
V_0 = {000}	OFF	OFF	OFF	ON	ON	ON	0	0	0	zero vector
V_1 = {100}	ON	OFF	OFF	OFF	ON	ON	$+V_{dc}$	0	$-V_{dc}$	active vector
V_2 = {110}	ON	ON	OFF	OFF	OFF	ON	0	$+V_{dc}$	$-V_{dc}$	active vector
V_3 = {010}	OFF	ON	OFF	ON	OFF	ON	$-V_{dc}$	$+V_{dc}$	0	active vector
V_4 = {011}	OFF	ON	ON	ON	OFF	OFF	$-V_{dc}$	0	$+V_{dc}$	active vector
V_5 = {001}	OFF	OFF	ON	ON	ON	OFF	0	$-V_{dc}$	$+V_{dc}$	active vector
V_6 = {101}	ON	OFF	ON	OFF	ON	OFF	$+V_{dc}$	$-V_{dc}$	0	active vector
V_7 = {111}	ON	ON	ON	OFF	OFF	OFF	0	0	0	zero vector

Table2: Switching states operation

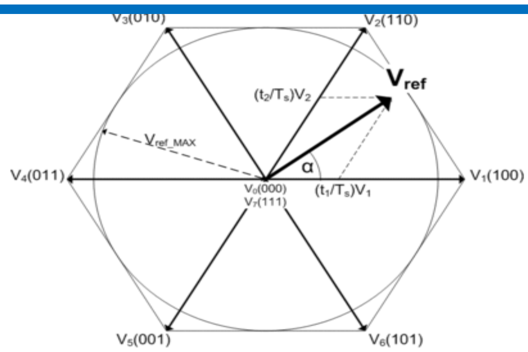

Fig 4: Voltage Vector diagram

A. Nomenclature:

Vs	Stator voltage vector.
φs (*φr*)	Stator (rotor) flux vector.
Te	Electromagnetic torque.
Rs	Stator resistance.
Ls (*Lr*)	Stator (rotor) inductance.
Lm	Magnetizing inductance.
σ	Total leakage coefficient,
σ	= 1− *L*2 *m/LsLr* .
p	Pole pair number.

Torque and Flux Estimation:

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

$$\frac{d\phi_s(t)}{dt} = v_s(t) - R_s i_s(t) \quad (6)$$

Maintaining *vs* constant over a sample time interval and neglecting the stator resistance, the integration of (8) yields

$$\Delta\phi_s(t) = \phi_s(t) - \phi_s(t-\Delta t) = \int_{t-\Delta t}^{t} v_s \Delta t. \quad \textbf{(7)}$$

Equation (7) reveals that the stator flux vector is directly affected by variations on the stator voltage vector. On the contrary, the influence of *vs* 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 behaviour is

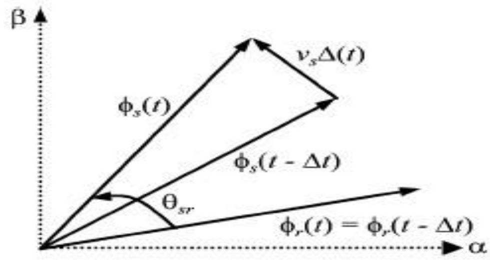

Fig5:Influence of Vs over *φs* during a simple interval Δt

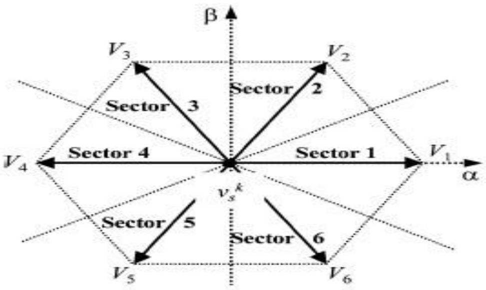

Fig6: Possible voltage changes Δv_s^k that can be applied from certain v_s^k

Illustrated in Fig. 6 The exact relationship between stator and rotor flux shows that keeping the amplitude of φs constant will produce a constant flux φr. Since the electromagnetic torque developed by an induction motor can be expressed by

$$T_e = \frac{3}{2} p \frac{L_m}{\sigma L_s L_r} \phi_s \phi_r \sin\theta_{sr} \quad (8)$$

it follows that change in θsr due to the action of *vs* allows 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.

IV. Voltage Vector Selection

Fig. 4 illustrates one of the 8 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

$$v_s^{k+1} = v_s^k + \Delta v_s^k \quad (9)$$

where Δ*vk s* = *{vi* |*i* = 1, . . . , 6*}*. Each vector *vi* corresponds to one corner of the elemental hexagon illustrated in gray and by the dashed line in Fig. 6. The task is to determine which *vk*+1 *s* will correct the torque and flux responses, knowing the actual voltage vector *vk s* , the*n* 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.

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. The proposed control algorithm was divided into two major tasks, which are independent and executed in cascade.

1) *First task*: It aims at the control of the electromagnetic state of the induction motor. The torque and flux instantaneous values and their variations will be taken into account for the space vector selection in the *α–β*. Once the space is chosen, the phase levels sequence can be selected. To ensure this task, one should detect the space vector position in the *α–β* frame (*Qk* at sampling time *k*). The algorithm must then select the next position *Qk*+1 to be achieved before next sampling instant *k* + 1in order to reduce voltage steps magnitude.

2) *Second task:* It exploits the degree of freedom related to the multilevel topology to choose the phase levels sequence that synthesizes the voltage vector selected previously. There are several phase levels sequences that are able to generate the same vector .this degree of freedom can, therefore, be exploited to reduce voltage steps magnitude according to one of the following criteria: a) minimize the commutation number per period; b) distribute commutations for the three-phases per period; or c) choose a vector which minimizes the homopolar voltage. This task allows losses and torque ripple minimization.

V.MATLAB/SIMULATION RESULTS

5.1. Symmetrical Cascaded H-bridge multilevel inverter:

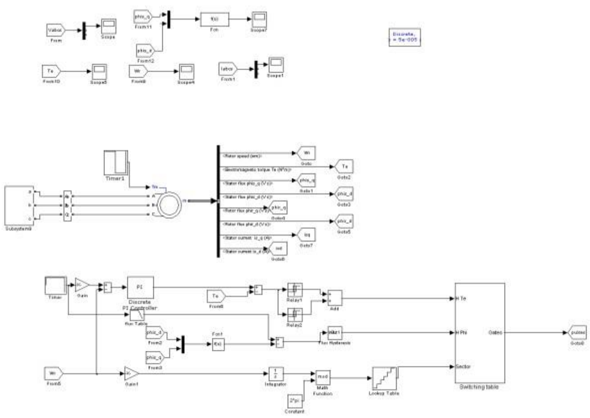

Fig7: Designing of circuit

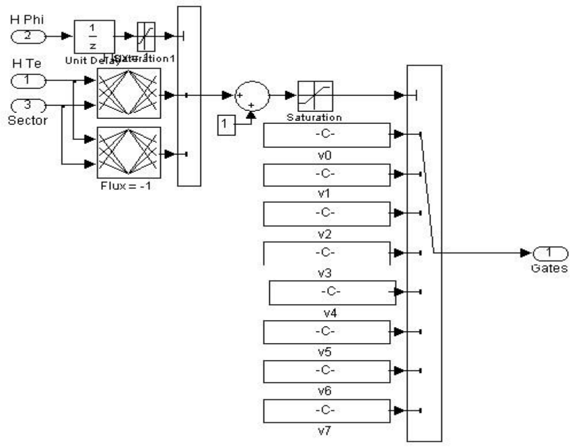

Fig8: Switching operation

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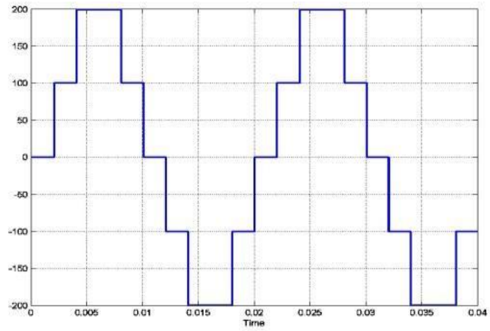

Fig.9: shows the symmetrical cascaded H-bridge five level multilevel inverter output voltage

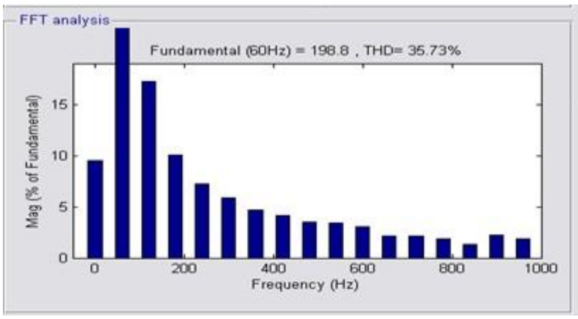

Fig10:THD value of the five level multilevel inverter using FFT analysis

5.2. Asymmetrical Cascaded H-bridge Seven level multilevel inverter:

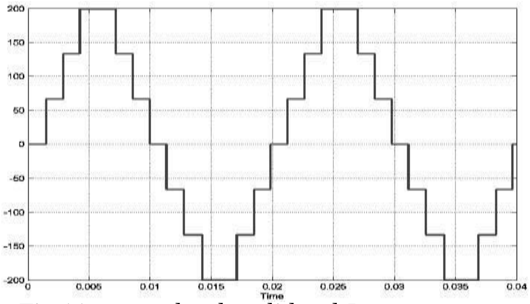

Fig.11: seven level mulitlevel Inverter output voltage

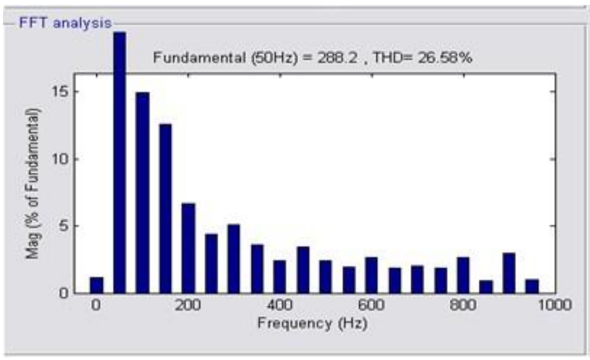

Fig.12. THD value of the seven level asymmetrical cascaded H-bridge multilevel inverter using FFT analysis

5.3. Asymmetrical Cascaded H-bridge nine level multilevel inverter:

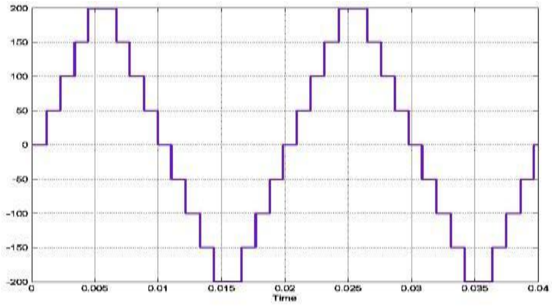

Fig.13 shows the asymmetrical cascaded H-bridge nine level multilevel inverter output voltage

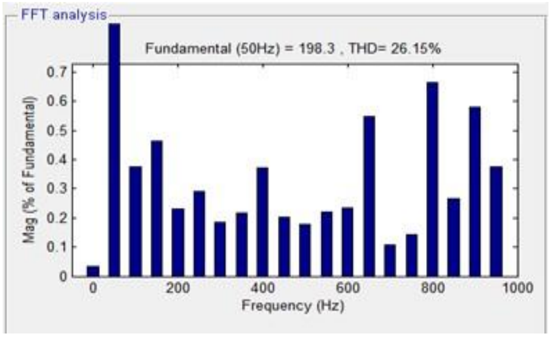

Fig.14 THD value of the nine level asymmetrical cascaded H-bridge multilevel inverter using FFT analysis

5.4 Asymmetrical Cascaded H-bridge eleven level multilevel inverter:

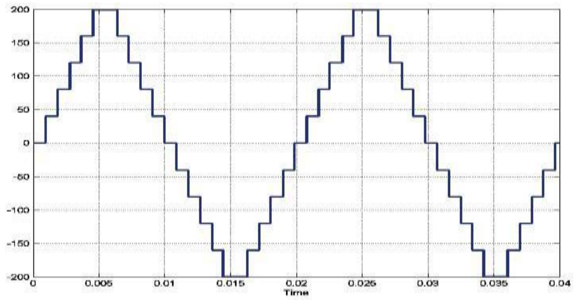

Fig.15: shows the asymmetrical cascaded H-bridge eleven level multilevel inverter output voltage

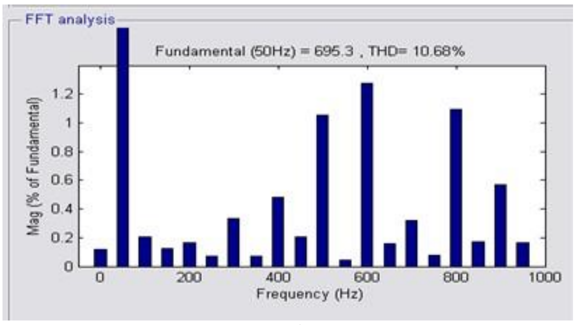

Fig.16: THD value of the Eleven level asymmetrical cascaded H-bridge multilevel inverter using FFT analysis

Number of levels	THD Value
5-level	35.73%
7-level	26.58%
9-level	26.15%
11-level	10.68%

Table 3: Comparison of number of levels and THD VALUES

V. CONCLUSION

This paper dealt with a comparison study for a cascaded H-bridge multilevel inverter using flexible control technique vector space pulse width modulation and also Direct Torque Control method. Indeed, symmetrical and asymmetrical arrangements of five- level, seven-levels, nine-level and eleven-level 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 experiments shows that an asymmetrical configuration provides nearly sinusoidal voltages with very low distortion, using less switching devices. In addition, torque ripples are greatly reduced: asymmetrical 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. With increase in number of levels the THD value is decreased from 35.78% to 10.68% and thus efficiency is increased and future scope is instead of placing DC link between conversion between rectifier and inverter replace with renewable energy sources like solar energy.

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