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Performance Analysis of Three Phase Cascaded Multi-level Inverter (CMLI) for Induction Motor Drives

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ABSTRACT

Traditional high-frequency pulse width modulation (PWM) inverters for motor drives have several problems associated with their high switching frequency which produces high voltage change (dv/dt) rates. Multilevel inverters solve these problems because their devices switch at the fundamental frequency. The concept of multilevel voltage source inverter is explained. In this paper the cascade inverter is a natural fit for induction motor drives because of the high VA ratings possible and it uses several levels of separate equal dc voltage sources which would be available from batteries or fuel cells. The switching angles of switch devices are determined by optimized harmonic stepped waveform (OHSW) technique to reduce the output harmonics of cascade multilevel inverter (CMLI) for induction motor is proposed, as a result the efficiency of system has improved. Simulation results show the superiority of this inverter over 2-level inverter and were carried out using ORCAD package.

Keywords: Three phase CMLI, OHSW, HF, HLF, DF, THD.

تحليل اداء عاكس متتالي متعدد المستويات ثلاثي الاطوار لسوق محرك حثي

الخلاصة

عواكس تضمين عرض النبضة (PWM) التقليدية لسوق محرك لها مشاكل متعدد مرافقة مع تردد التشغيل العالي والتي تسبب معدل تغير في الجهد مع الزمن (dv/dt) العالي. لحل تلك المشاكل استخدمت عواكس متعددة المستويات وذلك لأمتلاكها عناصر الكترونية تشغل عند التردد الاساسي. تم عرض مفهوم عاكس مصدر الفولتية متعدد المستويات. العاكس المتتالي ملائم لسوق محرك حثي لأنه ذات قدرة مقننة عالية ويستخدم مستويات متعدد من مصادر فولتية مستمرة متساوية ومنفصلة التي تكون متوفرة من بطارية او خلايا وقود. العاكس متعدد المستويات نوع المتتالي استخدام في هذا البحث بتقنية الشكل الموجي المتدرج المثالي للمحتوى التوافقي (OHSW) في حساب زوايا التشغيل وتقليل توافقيات الخرج لسوق محرك حثي وتحسين كفاءة المنظومة. نتائج المحاكاة بينت تفوق هذا العاكس على عاكس ذو مستويين، استخدمت الحقيبة ORCAD .

INTRODUCTION

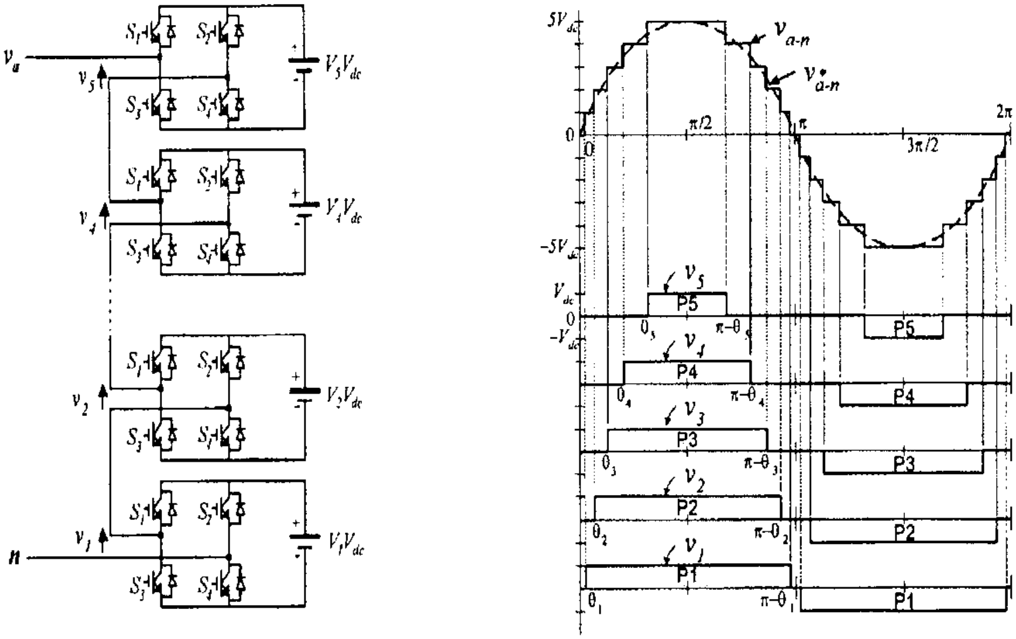
Nowadays, multilevel inverters (MLIs) have achieved increasing contribution in high-performance applications. Recently, for high-performance power application, multilevel converters are widely used such as static var compensators, induction motor drives & active power filters [1].The advantages of multilevel inverters are as follows:
(i) because of the staircase output voltage waveforms, THD &the dv/dt is lowered.(ii) efficiency is increased because they can be switched at low frequency.(iii) common mode voltages are reduced & hence the stresses on the motor bearings are reduced.(iv) the input current drawn by them has low distortion.(v)there exists no EMI problem [2]. Therefore, MLIs is more efficient than a two-level PWM inverter [3].The topologies of multilevel inverters are classified into three types, that is the flying capacitor, diode clamped & cascaded multilevel inverters(CMLI) [4].The topology cascaded multilevel inverter is advantageous with respect to other topology as voltage level can be easily increasing the number of dc sources [5].

Three, four & five level inverter drive systems which have used some form of multilevel PWM as a means to control the switching of the inverter section have been investigated in the literature [6, 7]. Multilevel PWM has lower (dv/dt) than that experienced in some two-level PWM drives because switching is between several smaller voltage level .However, the switching losses & voltage total harmonic distortion (THD) are still relatively high for these proposed schemes; the output voltage (THD) was reported to be (19.7%) for a 4-level PWM inverter [8] & (8.28%) for an 9-level PWM inverter without the use of any filtering components [4].

This paper deals with the performance of 7-level CMLI is used to feed the three phase induction motor drives through harmonic analysis & simulated using ORCAD program then the results are presented. CMLI employing OHSW technique is also simulated where devices are switched only at the fundamental frequency (50Hz) & the corresponding results are presented. The frequency spectrum for the outputs is analyzed to study the reduction in harmonics. For evaluation of power quality in this paper, the total harmonic distortion factor (THD), distortion factor (DF), harmonic loss factor (HLF) & harmonic factor (HF) are generally used. For a given voltage the above factors are functions of the waveform [9].The inverter output line voltage (THD), (DF), (HLF), (HF) can be reduced to (6.5%),(0.05%),(0.91%),(25%) respectively without the use of any filtering components. That is, the power quality can be improved.

CASCADED MULTILEVEL INVERTER (CMLI)

A CMLI consists of a series of bridge (B) (single phase bridge) inverter units. The general function of this multilevel inverter (MLI) is to synthesize a desired voltage from several separate dc sources (SDCSs), which may be obtained from batteries, fuel cells, or solar cells. Fig (1-a) a shows the basic structure of a single phase CI with SDCSs. Each inverter level can generate three different voltage outputs,($+V_{dc}$, 0, $-V_{dc}$) by connecting the dc source to the ac output by different combinations of four switches (S_1, S_2, S_3, S_4).To obtain ($+V_{dc}$),switches (S_1&S_4) are turned on, whereas ($-V_{dc}$) can be obtained by turning on switches (S_2&S_3).By turning on (S_1& S_2)or(S_3&S_4) the output voltage is 0.The ac outputs of each of the different (BI) levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs. The number of output phase voltage levels (m) in a CI is defined by (m=2s+1), where (s) is the number of separate dc source. An example phase voltage waveform for an 11-level CBI with (5 SDCs) & 5 bridges is shown in Figure(1-b).The phase voltage $V_{an}=V_{a1}+V_{a2}+V_{a3}+V_{a4}+V_{a5}$ [9].



(a) (b)

Figure (1) single phase MLCBI (a) circuit diagram (b) output waveform of 11-level phase voltage.

The three phase CIs can be connected in wye as shown in Figure (2) or in delta. One of the main advantages of CI is that the series of bridges makes for modularized layout & packaging. This will enable the manufacturing process to be done more quickly & inexpensively. Also, redundant voltage levels can be included in an application design so that the inverter can still operate even with the loss of one level. This enables the MLI to continue to function even when there is a problem with one of the dc sources or with one of the power electronics devices that make up the bridge [10].

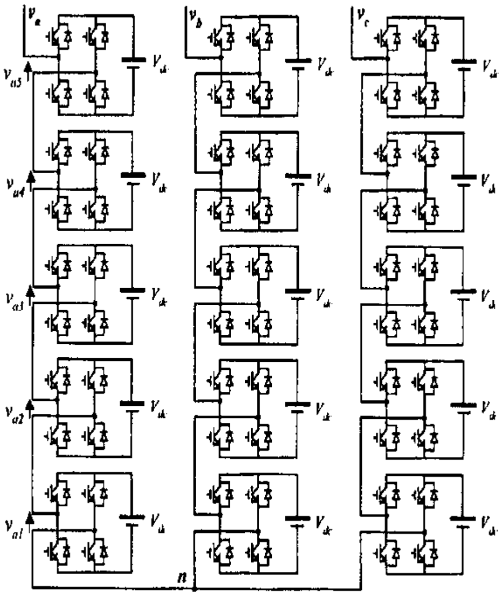


Figure (2) 11-level wye –configured three phases CI.

HARMONIC ELIMINATION (OHSW) TECHNIQUE FOR CMLI

The general harmonic elimination technique for MLI is referred in the literature to as "optimized harmonic stepped waveform OHSW". Its objective is to reduce the total harmonic distortion (THD) in the output voltage. The basic concept of this reduction is to elimination specific harmonics, which are generally the lowest orders, with an appropriate choice of switching angles. This is realized by adapting, skillfully, the idea of the selective harmonic eliminated PWM (SHE PWM) for 3-level inverter control based on the unipolar PWM switching scheme [11] to a generalized ML waveform synthesized from several levels of dc voltages.

Because of the symmetries of the chosen generalized waveform shown in Figure (1-b), only the odd harmonics exist. For this reason, its Fourier coefficients, which are calculated as the simple sum of the coefficients of all its rectangular waves, are given by the following equation:

$$a_n = \frac{4}{np} \sum_{k=1}^{S} V_{dck} \cos(n\,\alpha_k) \qquad ...(1)$$

Assuming a regular staircase waveform ($V_{dc1}=V_{dc2}=\ldots=V_{dcS}=V_1$),
This equation becomes:

$$a_n = \frac{4Vdc}{np} \sum_{k=1}^{S} \cos(n\alpha_k) \qquad \ldots(2)$$

Where (V_{dc}) is the voltage amplitude of the dc source (dc supply voltage); (n) is an odd harmonic order ;(S) is the number of dc sources or bridge cells;(α_k) are the optimized harmonic switching angles per quarter cycle.
Evidently, these angles must, constantly satisfy the basic constraint:

$$\alpha_1<\alpha_2<\alpha_3<\ldots..<\alpha_s< \pi/2 \qquad \ldots (3)$$

The amplitude of any harmonic can be obtained by setting equation (2), with respect harmonic, equal to pre-specified value. But based on the performance criteria, this equation can be solved for (s) variables,$\alpha_1$to α_s ,by:

- Either, equation (s) predominate lower frequency harmonics to zero in order to cancel it.
- Or provide for voltage control with simultaneous harmonics elimination, i.e. equating (s-1) lower order harmonics to zero & assigning a specific value to the fundamental component. This approach is the proposed & investigated in this paper.

Basically, the lowest odd harmonic components should be removed from a single phase system, whereas in the three phase system, they are the lowest non-triplen harmonic components that need to be eliminated. Thus, to eliminate (s-1) harmonics from the output voltage inverter, (s) switching angles need to be known. It implies, mathematically, that (s) equations formed from equation (2) are necessary. These equations, after some calculations, can be written as:
For the single phase system:

$$\cos(\alpha_1)+ \cos(\alpha_2)+ \ldots+ \cos(\alpha_s)=sm\pi/4$$
$$\cos(3\alpha_1)+ \cos(3\alpha_2)+ \ldots+ \cos(3\alpha_s)=0$$
..
..
$$\cos(n\alpha_1)+ \cos(n\alpha_2)+ \ldots+ \cos(n\alpha_s)=0 \qquad ...(4)$$

For the three phase system:

$$\cos(\alpha_1)+ \cos(\alpha_2)+ \ldots+ \cos(\alpha_s)=sm\pi/4$$
$$\cos(5\alpha_1)+ \cos(5\alpha_2)+ \ldots+ \cos(5\alpha_s)=0$$
.
.
$$\cos(n\alpha_1)+ \cos(n\alpha_2)+ \ldots+ \cos(n\alpha_s)=0 \qquad \ldots(5)$$

Where (n) is an odd number for the single phase system, different from three& its multiples for the three phase system ;($m=V_1/sV_{dc}$) is the modulation index & (V_1) is the amplitude of the fundamental component[12].
The resolution of these two systems, which are nonlinear, is achieves by iterative method in MATLAB optimization toolbox.

The optimization technique has been used to minimize the harmonic content of the inverter output voltage. The best compromise between efficiency & quality of the inverter operation is achieved by the optimal switching pattern technique.

COMPUTATIONAL RESULTS

By using the eq.(5),the switching angles are determined for the three phase 7-level CMLI using OHSW technique to harmonics elimination of 5th ,7th &MATLAB package is employed. Table (1) at appendix (A) shows the switching angles of three phase 7-level CMLI. Figure (3-a) in appendix(A) shows the linear relationship between switching angles & modulation index(m).The output waveform of an 7-level CMLI is shown in fig(3-b).This means that if the inverter output is symmetrically switched during the positive half cycle of the fundamental voltage to V_1 at (11.617°) ,V_2 at (31.1783°),V_3 at(58.5774°) when modulation index of (m=1.0) & similarly in the negative half cycle to -V_1 at (191.617°) , -V_2 at (211.1783°), -V_3 at (238.577°) the output voltage of the 7-level CMLI will not contain the 5th ,7th harmonic components & 11th the lowest harmonic component appearing in line output voltage of three phase 7-level CMLI .

The output of MLIs contains harmonics & the quality of an MLI is normally evaluated by using performance factors. An evaluation criterion was measured by:

- Harmonic factor(HF)

$$HF_n=\sqrt{\left[\left(\frac{Vn}{V_1}\right)^2-1\right]} \qquad .... (6)$$

- Harmonic loss factor (HLF)
-

$$HLF = \frac{1}{V_1}\sqrt{\sum_{n=5}^{n=125}\left[\frac{V_n}{n}\right]^2} \qquad \dots (7)$$

- Total harmonic distortion factor (THD)

$$THD=\frac{1}{V_1}\sqrt{\sum_{n=5}^{n=125}\left(V_n\right)^2} \qquad ... (8)$$

- Distortion factor (DF)

$$DF=\frac{1}{V_1}\sqrt{\sum_{n=5}^{n=125}\left[\frac{V_n}{n^2}\right]^2} \qquad \dots (9)$$

Where:

V_1: fundamental voltage (rms)
V_n: harmonic voltage (rms)

n: order of harmonics.[13]
Usually, n=125 is reasonably accepted.

SIMULATION RESULTS

The simulation results of phase voltage &line voltage waveforms were measured after running ORCAD program & are shown in Figure (5) with different modulation index (0.6,0.8,1.0) at appendix(B).The resulting line voltage is an 7-level staircase waveform. This means that an m-level CMLI has an m-level output phase voltage & a (2m-1) level output line voltage.

The frequency spectrum of line voltage waveforms is shown in Figure (6) with different modulation index(0.6,0.8,1.0) at appendix (B).Note that the 5th & 7th harmonics are eliminated as predicted therefore the 11th (550Hz) harmonic will appear in the spectrum as a first harmonic. From Figure (6) at appendix (B) the amplitude of the fundamental component of phase voltage waveform is (111Vpeak), which is (61.7%) of the dc source value (180V) at modulation index(m=0.6),then (144.89Vpeak), which is (80%) of the dc source value (180V) at modulation index (m=0.8),& (180Vpeak), which is (100%) of the dc source value (180V) at modulation index(m=1.0).It can be seen that increasing (m), causes increases the amplitude of the fundamental component of output voltage. From this figure, when the lower-order harmonics amplitudes vary inversely with the increasing of the modulation index (m). The lower-order harmonics have the larger magnitude when modulation index (m=0.6), which are more harmful to motor.

The load current drawn by an inductive-resistive load (motor) as shown in Figure (4) produced by the line voltages waveform of Figure (5) at appendix (B) are shown in Figure (7) at appendix (B) ,then the current waveform becomes nearly sinusoidal with minimum distortion & ripple. The frequency spectrum of the load current waveforms with different modulation index is shown in Figure (8) at appendix (B) the amplitude of the fundamental component of load current waveform is (31.41mApeak) at modulation index (m=0.6), then (41.68mApeak) at modulation index (m=0.8)& (52mApeak) at modulation index(m=1.0). It can be concluded from these figures that the ripple & distortion in the motor current will decrease with increasing modulation index (m) and as result the amplitude of the fundamental component of load current will increase with increasing modulation index (m).

Note that the harmonic content of the load current significantly reduced compared to harmonic content the voltage due to filtering by the motor ′s inductance act a low pass current filter. As a result the current waveforms become more sinusoidal.

Evaluation of the inverter performance can be calculated from the performance factors (HF, HLF, DF &THD) in equations (6, 7, 8, 9) as shown in Table (3) at appendix (C) have been plotted versus the modulation index. Figure (9) at appendix (C) illustrates the relationship between this factors & modulation index. We can see from the curves that the optimum value of (m) is about (1.0) to get minimum harmonic content & minimum distortion. Therefore, the increasing of (m), causes reduction in distortion & improves the quality of the inverter output waveform.

By using the equivalent circuit of the motor & the performance equations [14], it can be easy to analyze the performance of the motor operated on an OHSW 7-level CMLI, & using the equations to calculate the harmonic current amplitude to get the current spectrum for motor current as shown in Figure (10) with different modulation index at appendix (D), increasing of modulation index causes push spectrum to high frequency region, then causes increase of the motor impedance, therefore the harmonic currents decrease for constant harmonic voltage amplitude. Decreasing of harmonic currents causes decreasing of torque pulsations, therefore increasing of modulation index means decreasing of torque pulsations as shown in Figure (11) for motor torque spectrum with different modulation index at appendix (D). It can be seen that, pulsations torques are obtained at all even multiples of supply frequency. Noticing that, the torque pulsations amplitude decreases with increasing of modulation index. When modulation index (m=1.0) multiple of torque pulsations will be suppressed, then the motor will behave just like motor supplied directly by sinusoidal power supply, so that the motor will be more quite with higher (m).

CONCLUSIONS

- A CMLI has been proposed for use in induction motor drives. Simulation has shown that with a control strategy that operates the switches at fundamental frequency.
- The OHSW technique was successfully implemented for computing the switching angles for three phase 7-level CMLI & its enables to completely eliminates any number of harmonics to get highest quality motor drive with low distortion AC waveform.
- A CMLI should be operated with modulation index (m=1.0) , because the amplitude of fundamental of output voltage is (100%) of the dc source value .
- A complete performance analysis for 7-level CMLI induction motor drives has been presented, it is shown that a low output voltage (HF, HLF,DF,THD) .
- This system (three phase 7-level CMLI induction motor drives) has efficiency is much higher (> 93%) as shown inFigure (12) at appendix (D) because of minimum switching frequency.
- Additionally, the simulation results show that the output line voltage dv/dt is reduced by 7 times with 7-level CMLI as compared to a traditional 2-level PWM drive.
- The dramatic one order of magnitude reduction in dv/dt can prevent motor windings &bearings from failure.
- The best compromise between high efficiency & high quality of the CMLI operation is achieved by minimum switching frequency.
- This 7-level staircase output voltage waveform approaches a sinwave, thus having no common-mode voltage & no voltage surge to the motor windings.

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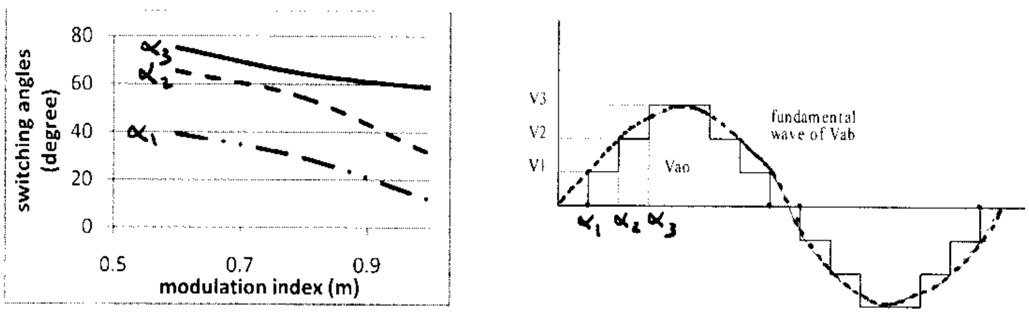
Appendix (A)

Table (1) the switching angles (in degrees) of 7-level CMLI.

m	$\alpha_1(^\circ)$	$\alpha_2(^\circ)$	$\alpha_3(^\circ)$
0.6	39.4298	58.5839	83.1042
0.8	29.2355	54.4383	64.4844
1.0	11.6817	31.1783	58.5774



(a) (b)

Figure (3) cascaded multilevel inverter (a) solution trajectories (b) phase & line output voltage waveform for 7-level.

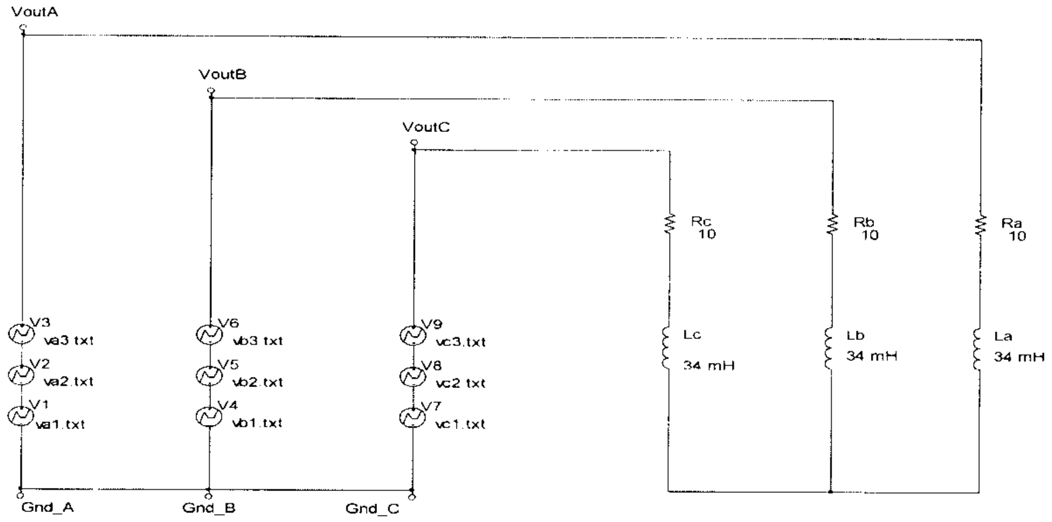
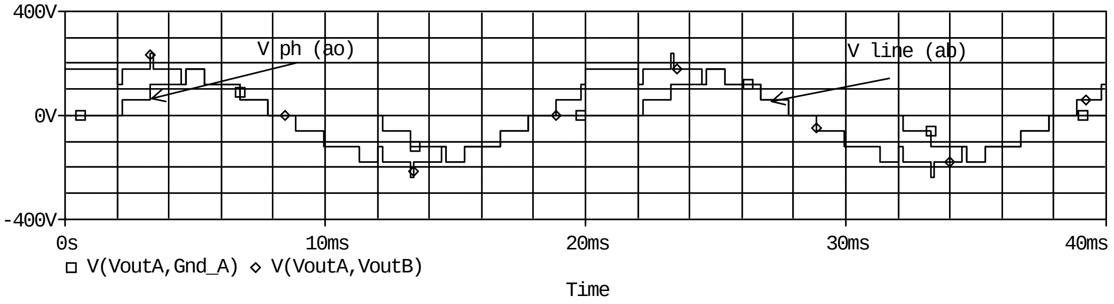


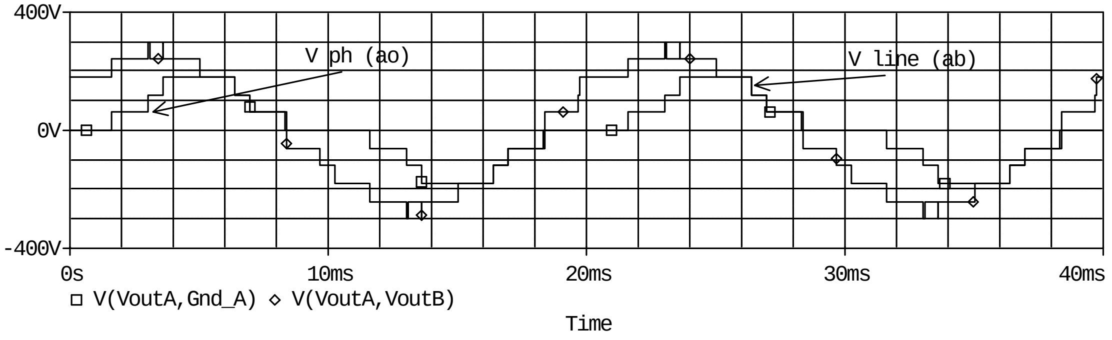
Figure (4) a schematic of a three phase 7- level cascaded multilevel inverter for motor drive.

Appendix(B)

(m=0.6)



(m=0.8)



(m=1.0)

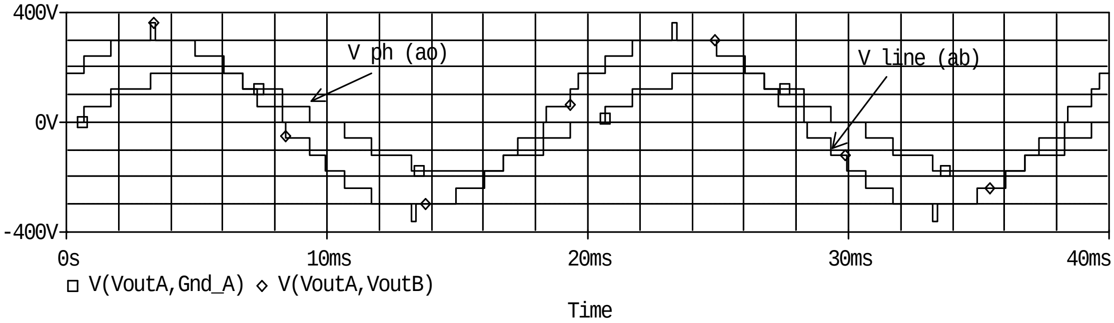
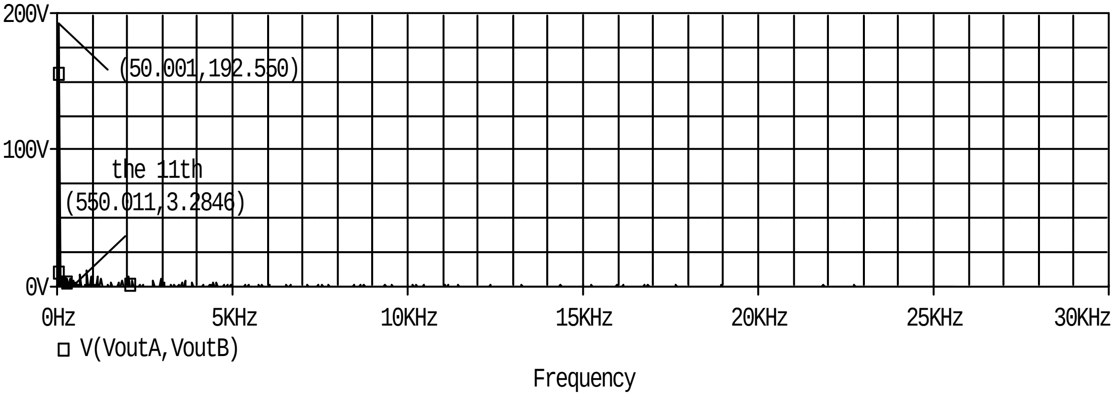
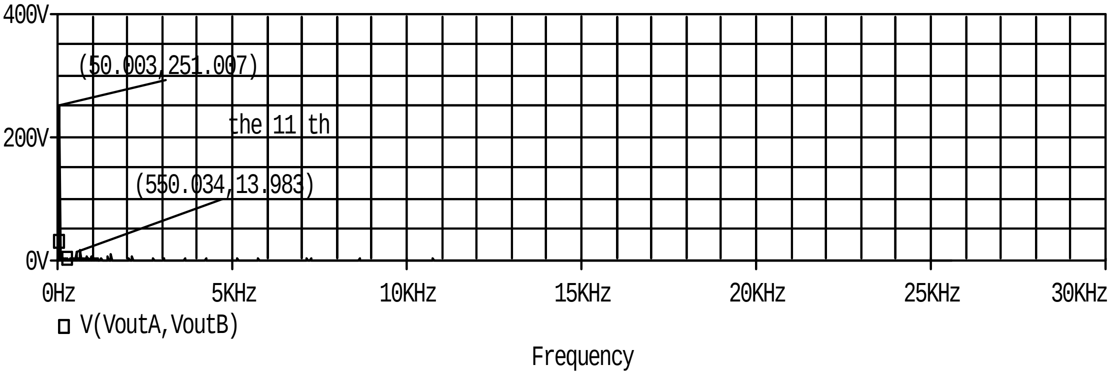


Figure (5) phase voltage & line voltage waveforms of OHSW three phase 7-level cascaded multilevel inverter with different modulation index (m).

(m=0.6)



(m=0.8)



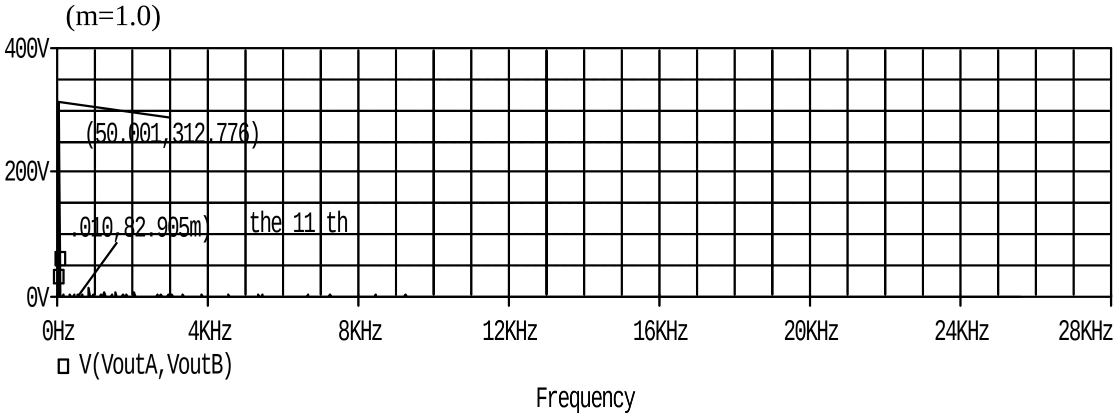


Figure (6) frequency spectrum of line voltage in detail of OHSW three phase 7-level cascaded multilevel inverter with different modulation index(m).

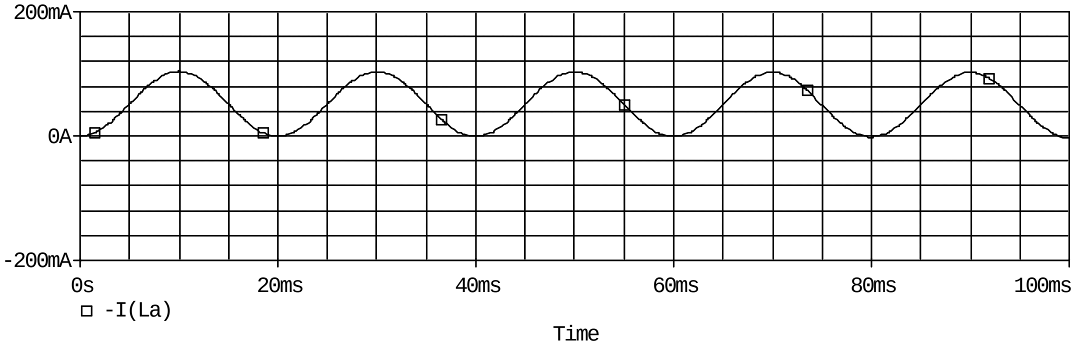
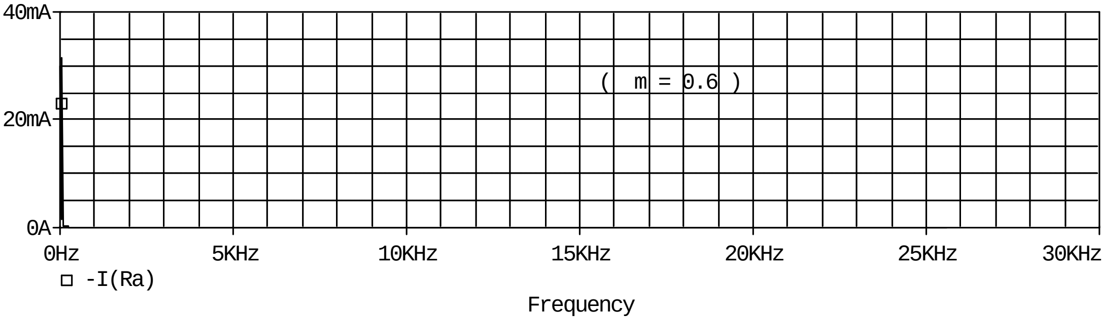


Figure (7) load current of OHSW three phase 7-level cascaded multi-level inverter with modulation index (m =1).



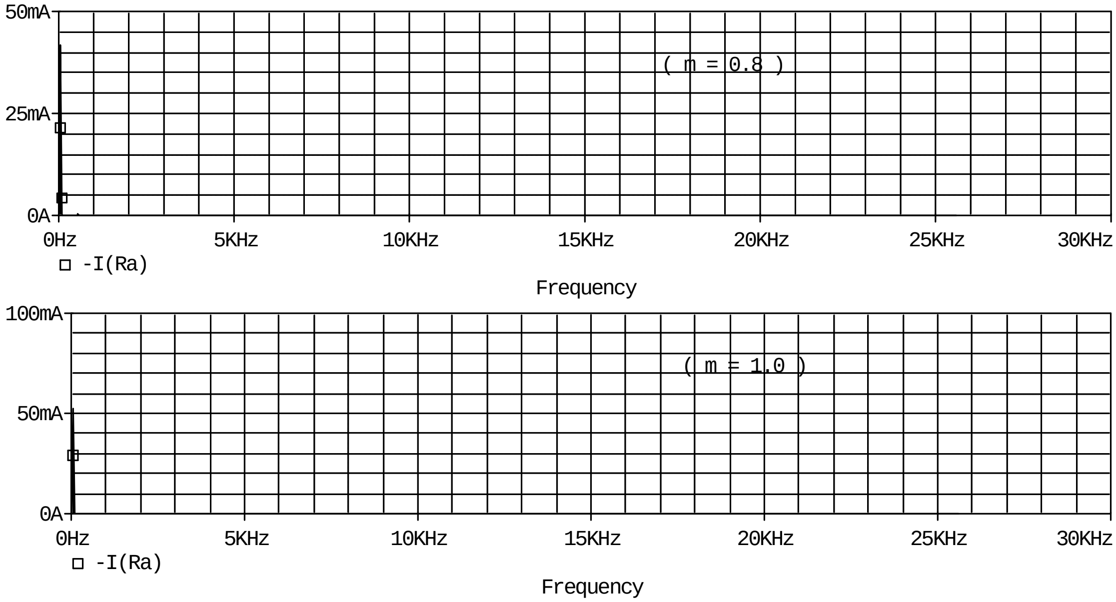


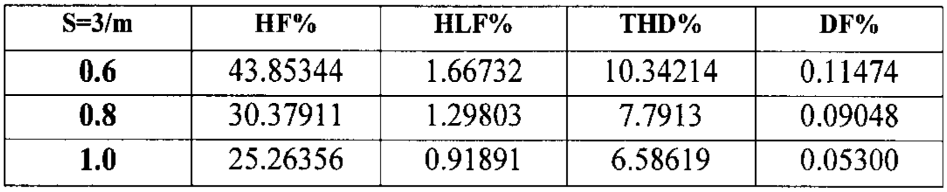
Figure (8) frequency spectrum of load current of OHSW three phase 7-level cascaded multilevel inverter with different modulation index(m).

Appendix (C)

Table (2) parameters of tested induction motor.

Magnetizing inductance (Lm)	61 mH
Stator leakage inductance (L_1)	1.9 mH
Rotor leakage inductance (L_2)	1.9 mH
Stator resistance (R_1)	0.6 ohm
Rotor resistance (R_2)	0.4 ohm
Voltage (V)	380/220
Current (I)	15 A
Power (P)	5 hp
Speed (nr)	1470 r/min
Frequency (F)	50 Hz
Slip (S)	0.02

Table (3) The value of performance factors (HF,HLF,THD,DF) of OHSW three phase 7-level cascaded multilevel inverter.



S=3/m	HF%	HLF%	THD%	DF%
0.6	43.85344	1.66732	10.34214	0.11474
0.8	30.37911	1.29803	7.7913	0.09048
1.0	25.26356	0.91891	6.58619	0.05300

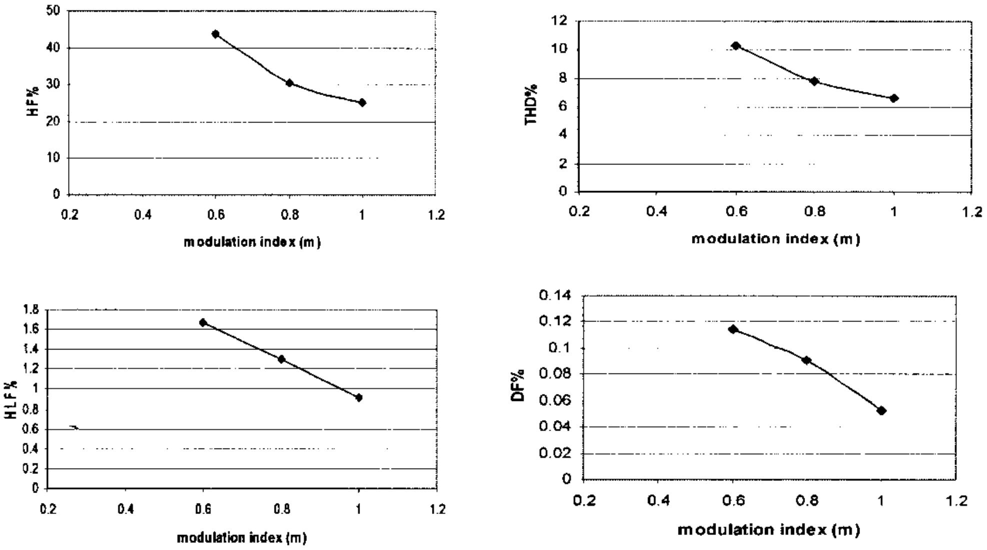


Figure (9) performance factors of OHSW three phase 7- level cascaded multilevel inverter as function of the modulation index (m).

Appendix (D)

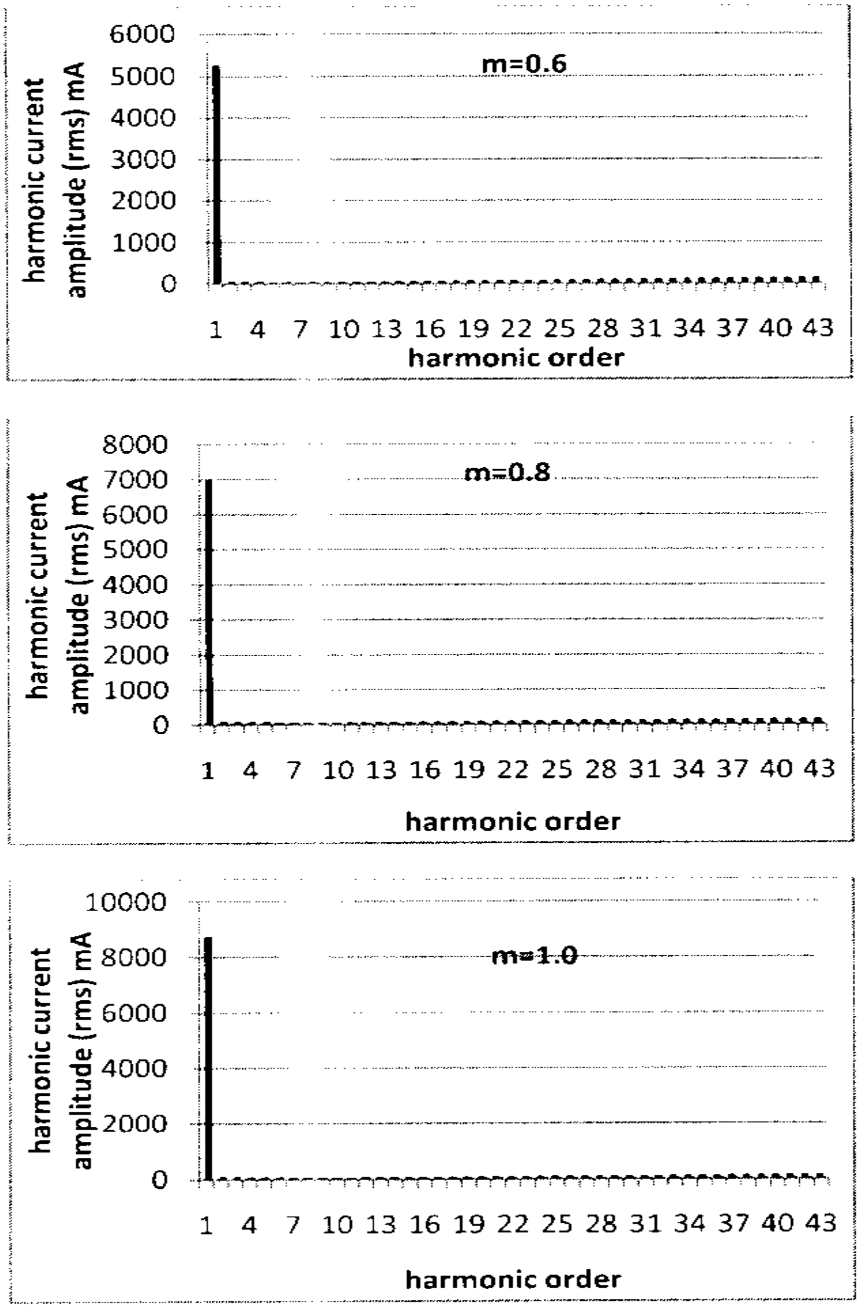


Figure (10) motor line current spectrum of OHSW three phase 7- level cascaded multilevel inverter with different modulation index (m).

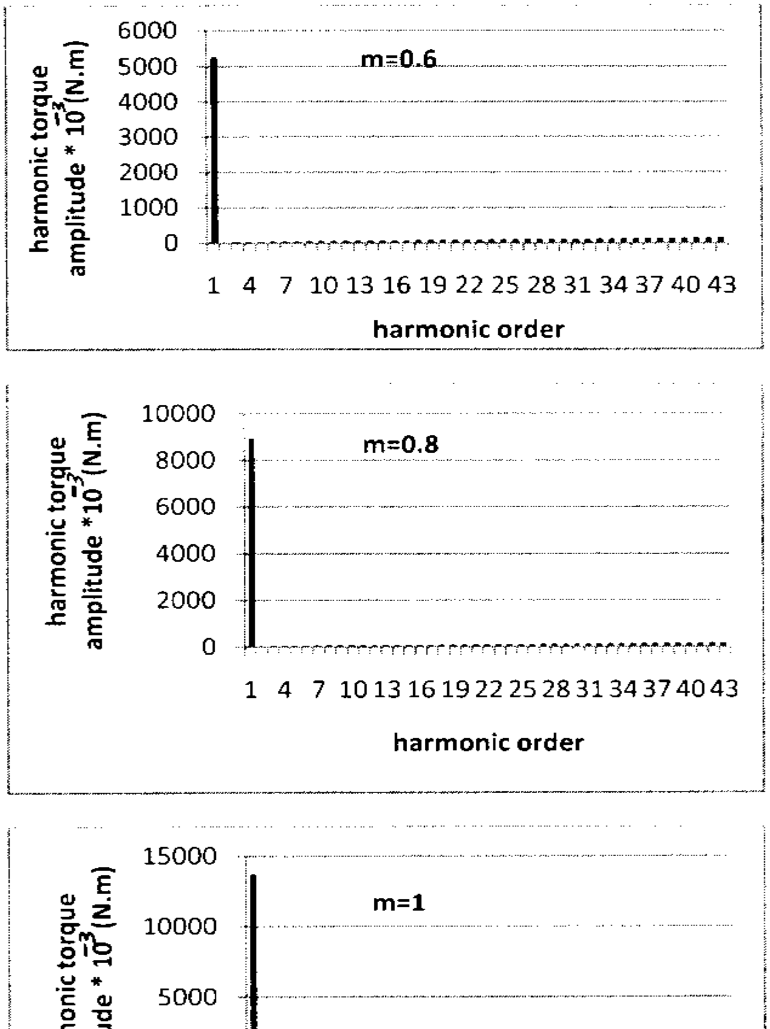


Figure (11) motor torque spectrum of OHSW three phase 7- level cascaded multilevel inverter with different modulation index (m).

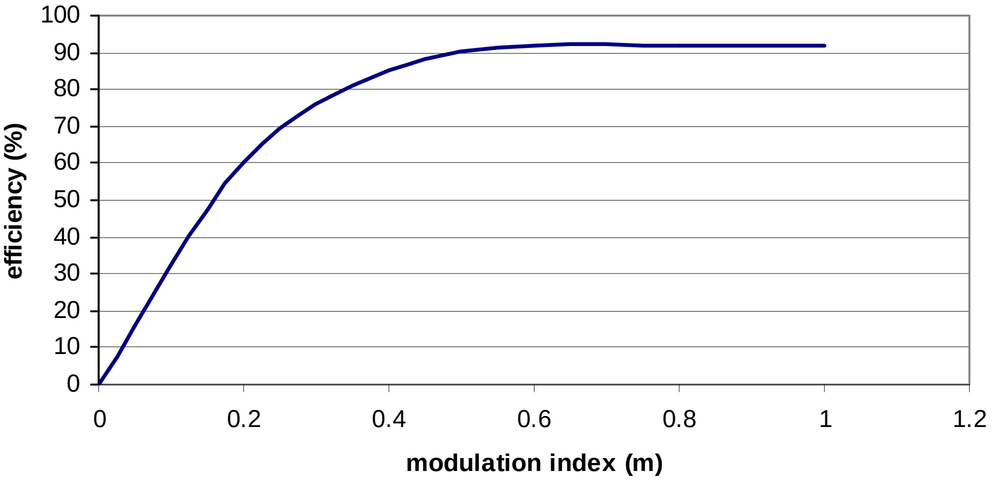


Figure (12) system efficiency (three phase 7-level CMLI induction motor drives) as a function of the modulation index (m).