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A Proposed Technique For Harmonic Reduction Of Three Phase Cascade Multilevel Inverter (Cmli)

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Abstract :

Inverters are widely used in many applications & the object of using the inverter is produce ac voltage with controllable magnitude & frequency. But the inverters where found in both the industrial motor drive industry & in the emerging distributed power generation industry, since these were essentially the only source of three phase inverters in the power range of interest. There are many types of multilevel inverters (MLI), but the cascaded multilevel inverter (CMLI) is most the favorite one for industrial applications. The three phase (CMLI) is used with optimization technique to suppress specific low-order harmonics or minimize total harmonic content & then improvement system efficiency .This technique of pulse width modulation (PWM) based on Walsh function harmonic elimination method. In this technique the harmonic amplitude of the inverter output voltage can be expressed as functions of switching angles. Thus, the switching angles are optimized by solving linear algebraic equations instead of solving nonlinear transcendental equations.

This technique is suitable for higher level of three phase cascade multilevel inverter (CMLI) where other existing methods fail to compute the switching angles due to more computational burden. For the number of output voltage levels where multiple solutions exist, the solutions where produce least total harmonic distortion (THD) in the output voltage is chosen.

As compared with previous work, the decrease in the THD can be reduced to (3%) in case of the proposed technique. In this paper, significant decrease in THD is obtained by solving linear algebraic equations for switching angles with system is three phases instead of solving nonlinear transcendental equations for switching angles with system is single phase. The proposed technique is implemented on a three phase cascade multilevel inverter (CMLI). Simulation results are presented using ORCAD package.

Keywords: multilevel inverter (MLI), cascaded multilevel inverter (CMLI), pulse width modulation (PWM), Walsh function.

تقنية مقترحة للتخلص من التوافقيات لعاكس متتالي متعدد المستويات ثلاثي الأطوار

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الخلاصة:

تستخدم العاكسات على نطاق واسع في العديد من التطبيقات، الهدف من استخدام العاكس هو توليد فولتية متناوبة ذات مقدار وتردد يمكن التحكم بهما .هناك أنواع عديدة من عاكس متعدد المستويات ولكن العاكس المتتالي هو الأكثر استخداماً في التطبيقات الصناعية.العاكس المتتالي متعدد المستويات ثلاثي الأطوار استخدم في هذا البحث بتقنية تضمين عرض النبضة جديدة معتمدة على طريقة التخلص من التوافقيات باستخدام دالة والش .باستخدام هذه التقنية فان مقدار التوافقيات لفولتية خرج العاكس يمكن التعبير عنها كدوال لزوايا التشغيل. لذلك حيث يمكن تحسين حساب مقدار زوايا التشغيل ليكون بحل معادلات جبرية خطية بدلا من حل معادلات متسامية(transcendental) غير خطية.

ان التقنية المستخدمة ملائمة لمستويات عديدة لعاكس متتالي متعدد المستويات ثلاثي الاطوار تصل الى (65) مستوي بينما اثبت التقنيات الأخرى عدم كفاءتها في حساب زوايا التشغيل لمثل هذه المستويات وذلك لزيادة عامل التشوه الكلي(THD) للفولتية الخارجة للعاكس.

حيث تمت المقارنة مع دراسة سابقة بين النقصان في عامل التشوه الكلي(THD) يمكن ان يقل (3%) في حالة التقنية المقترحة. في هذا البحث تم الحصول على نقصان واضح في عامل التشوه الكلي(THD) بحل معادلات جبرية خطية لزوايا التشغيل مع منظومة ثلاثية الأطوار بدلا من حل معادلات متسامية(transcendental) غير خطية مع منظومة أحادية الطور. إن التقنية المقترحة استخدمت عاكس متتالي متعدد المستويات ثلاثي الاطوار. استخدمت نتائج المحاكاة الحقيبة ORCAD .

1- Introduction

Numerous industrial applications have begun to require higher power apparatus in recent years. Power electronic inverters are becoming popular for various industrial drives applications. A multilevel inverter (MLI) is a power electronic system that synthesizes a desired output voltage from several levels of dc voltages as inputs. Recently, multilevel power conversion technology has been developing the area of power electronics very rapidly with good potential for further developments [1]. As a result; MLIs receive more & more attention from both academy & industry. This is because of some inherent advantageous features such as ability to operate in the medium to high voltage ranges, high power quality condition, improved quality of the output waveform with smaller output voltage steps which results in lower harmonic components & better electromagnetic compatibility [2]. Also it can operate at both fundamental switching frequency & high switching frequency PWM. It must be noted that lower switching frequency usually means lower switching loss & higher efficiency [1]. The concept of MLI is to produce a staircase output voltage using the available dc voltage sources. The higher the number of voltage level the better the output voltage quality [2]. The field applications include use in laminators, pumps, conveyors, compressors, fans, blowers & mills [1]. There are three well-known types of MLIs. These are the cascaded bridge (CB) multilevel inverter (MLI) with separate dc sources, the flying capacitor (FC) MLI, & neutral point clamped (NPC) MLI [1, 2]. Each of these topologies has a different mechanism for providing the voltage level. The first topology introduced was the series bridge design but several configurations have been obtained for this topology as well. Since this topology consists of series power conversion cells, the voltage & power levels may be scaled easily [1]. Final advantages of this topology that the dual nature of the MLI could be used to drive the motor in fault situations. If the primary (higher- voltage) MLI is inoperable, the motor load can be driven by the lower- voltage MLI with system re-configuration [3]. The bridge topology was followed by the diode-clamped inverter that utilized a bank of series capacitors. The flying-capacitor topology followed diode-clamped after few years. Instead of series connected capacitors, this topology uses floating capacitors to clamp the voltage levels [1].

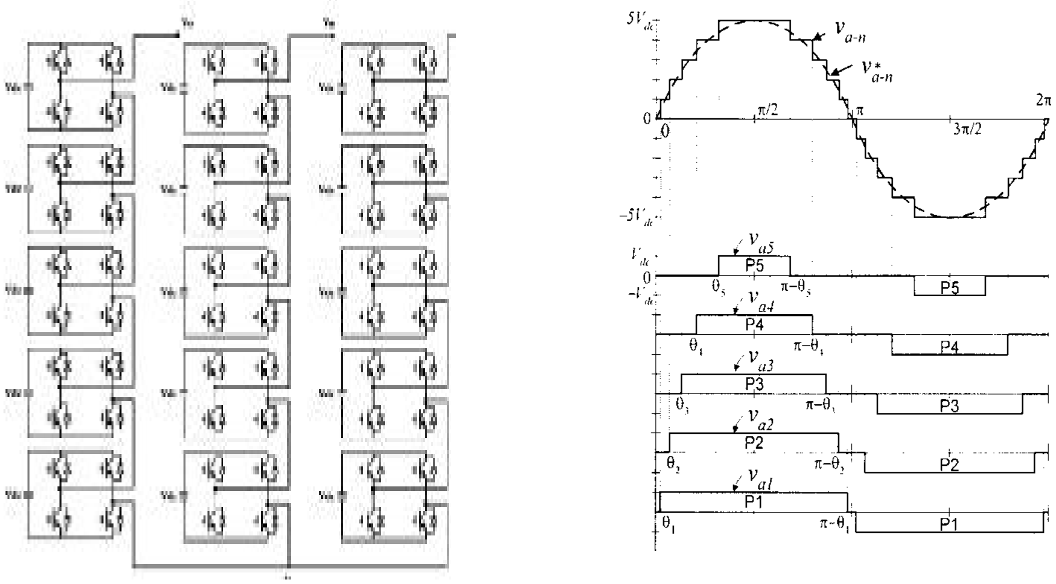
2- Cascaded multilevel inverter (CMLI)

A cascaded multilevel inverter (CMLI) made up from series connected single bridge inverter, each with their own isolated dc bus. This MLI can generate almost sinusoidal waveform voltage from several separate dc sources, which may be obtained from solar cells, fuel cells, batteries, ultra capacitors, etc. this type of converter does not need any transformer or clamping diodes or flying capacitors .

Each level can generate three different voltage outputs +Vdc, 0, -Vdc by connecting the dc sources to the ac output side by different combinations of the four switches. The output voltage of an m-level inverter is the sum of all the individual inverter outputs. Each of the bridges active devices switches only at the fundamental frequency & each bridge unit generates a quasi-square waveform by phase –shifting its positive & negative phase legs switching timings. Further, each switching device always conducts for 180 °(or half cycle) regardless of the pulse width of the quasi-square wave so that this switching method result in equalizing the current stress in each active device.

This topology of inverter is suitable for medium to high voltage & high power inversion because of its ability of synthesize waveforms with better harmonic spectrum &low switching frequency. Fig (1-a) shows the three phase structure of a cascaded 11-level inverter with five bridge inverters connected in series on each phase [4].

The number of output voltage levels in CMLI is then 2N+1, where N is the number of dc sources in phase one. An example phase voltage waveform for 11-level CMLI with five SDCSs (N=5) is shown in fig (1-b).The output phase voltage is given by ($V_{an}=V_{a1}+ V_{a2}+ V_{a3}+ V_{a4}+ V_{a5}$). With enough level & an appropriate switching algorithm, the MLI results in an output voltage is almost sinusoidal[5].



(a) **(b)**

Fig (1) Cascaded 11-level inverter. (a) Three phase structure of CMLI. (b)Output waveform

3- Mathematical model of switching for the CMLI

Walsh functions for an order set of rectangular waveforms taking only two amplitude +1 & -1 over one normalized frequency period. The Walsh functions form a complete orthogonal set; hence, Walsh functions can be used to represent signals in the same way as the Fourier series. Since the sinusoidal wave has quarter- symmetry, it is assumed that the PWM output waveforms $f(t)$ have unit amplitude & quarter-wave symmetry. Using Fourier series expansion the output waveform $f(t)$ can be expressed as follows:

$$f(t) = \sum_{k=1}^{k} A_{2k-1} \sin[(2k-1)\omega_1 t] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where $A_{2k-1} = \frac{2}{T}\int_0^T f(t)\sin[(2k-1)\omega_1 t]\,dt$

$$= \frac{8}{\pi}\int_0^{\pi/2} f(t)\sin[(2k-1)\omega_1 t]\,d(\omega t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

However, it is difficult to compute the harmonic amplitudes of $f(t)$ directly from eq. (2) because the inverter output waveform $f(t)$ is unknown.

Walsh functions, which have only two amplitudes +1 & -1 over one normalized time period can also be used to express the PWM output waveform $f(t)$ as:

$$f(t)=\sum_{n=1}^{N} W_{4n-3} WAL(4n-3,t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where $W_{4n-3}=\int_0^1 f(t)\, WAL(4n-3,t)dt \ldots\ldots\ldots\ldots\ldots\ldots (4)$

The W_{4n-3} is the Walsh coefficient of the inverter output voltage. Only the $(4n-3)$ order Walsh functions are used because of the quarter-wave symmetry of the inverter output voltage.

By replacing $f(t)$ in eq. (2) with eq. (3) the eq. becomes:

$$A_{2k-1}=\sum_{n=1}^{N} W_{4n-3}\left[\frac{8}{\pi}\int_0^{\pi/2} WAL(4n-3,\omega_1 t)\times \sin[(2k-1)\omega_1 t]d\omega t\right]$$

$$=\sum_{n=1}^{N} B_{2k-1,4n-3}\, W_{4n-3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where

$$B_{2k-1,4n-3}=\frac{8}{\pi}\int_0^{\pi/2} WAL(4n-3,\omega_1 t)\times \sin[(2k-1)\omega_1 t]d\omega t \ldots\ldots\ldots\ldots\ldots (6)$$

$B_{2k-1,4n-3}$ is the $(2k-1)$ harmonic coefficient of the $(4n-3)$ Walsh function. The values of $B_{2k-1,4n-3}$ coefficients can be calculated directly from the eq. (5)

$$A_1=B_{1,1}W_1+B_{1,5}W_5+B_{1,9}W_9+\ \ldots+B_{1,4N-3}W_{4N-3}$$

$$A_3=B_{3,1}W_1+B_{3,5}W_5+B_{3,9}W_9+\ \ldots+B_{3,4N-3}W_{4N-3}$$

. = …..

. = …..

$$A_{2K-1}=B_{2K-1,1}W_1+B_{2K-1,5}W_5+\ \ldots+B_{2K-1,4N-3}W_{4N-3} \ldots\ldots\ldots\ldots (7)$$

Eq . (7) in matrix form is

$$\begin{bmatrix} A_1 \\ A_1 \\ . \\ . \\ A_{2K-1} \end{bmatrix} = \begin{bmatrix} B_{1,1} & B_{1,3} & B_{1,9} \dots B_{1,4N-3} \\ B_{3,1} & B_{3,5} & B_{3,9} \dots B_{3,4N-3} \\ & & . \\ & & . \\ B_{2k-1,1} & B_{2k-1,5} & \dots B_{2k-1,4N-3} \end{bmatrix} \begin{bmatrix} W_1 \\ W_5 \\ . \\ . \\ W_{4N-3} \end{bmatrix} \dots\dots\dots\dots\dots (8)$$

By initializing the firing angles α_k , the Walsh function coefficients W_{4n-3} of the PWM output waveforms can be calculated from eq. (4). By sampling $f(t)$ with M equidistant points, the integral in eq. (4) is replaced by a summation

$$\begin{aligned} W_{4n-3} &= \int_0^1 f(t)\, WAL(4n-3,t)dt = \int_0^{1/M} f(t)\, WAL(4n-3,t)dt \\ &\quad + \int_{1/M}^{2/M} f(t)\, WAL(4n-3,t)dt + \cdots \dots\dots\dots\dots \\ &\quad + \int_{(M-1)/M}^{1} f(t)\, WAL(4n-3,t)dt \dots\dots\dots\dots\dots\dots (9) \end{aligned}$$

M, an integer power of two, is determined by the highest sequences-ordered component of the Walsh functions. The value of M is always chosen to be equal to $4N$, where N is given in eq. (3). Since $WAL(4n-3,t)$ is a constant value (+1 or -1) in each sampling interval, $WAL(4n-3,t)$ is replaced by $WAL(4n-3,m)$.Thus, eq. (9) becomes:

$$\begin{aligned} W_{4n-3} &= WAL(4n-3,0) \int_0^{1/M} f(t)\, dt \\ &\quad + WAL(4n-3,1) \int_{1/M}^{2/M} f(t)\, dt + \cdots \\ &\quad + WAL(4n-3,M-1) \int_{(M-1)/M}^{1} f(t)\, dt \\ &= \sum_{m=0}^{M-1} W(4n-3,m) \left[\int_{m/M}^{(m+1)/M} f(t)dt \right] \\ &= 4 \sum_{m=0}^{(\frac{M}{4})-1} W(4n-3,m) \left[\int_{m/M}^{(m+1)/M} f(t)dt \right] \dots\dots\dots\dots\dots (10) \end{aligned}$$

Although the exact values of switching angles $\alpha_1, \alpha_2, \ldots, \alpha_K$ are unknown, each of them must be initialized in sampling intervals $m_1, m_2, \ldots m_K$. So, each switching angle α_k is constrained within the following range

$(m_k/M) < \alpha_k < (m_k+1)/M$ for $k = 0, 1, \ldots k-1$ ....(11)

W_{4n-3} can be expressed as a function of switching angles $\alpha_1, \alpha_2, \ldots, \alpha_K$. Thus

$W_1 = C_{1,1}\alpha_1 + C_{1,2}\alpha_2 + \cdots C_{1,K}\alpha_K + D_1$

$W_5 = C_{5,1}\alpha_1 + C_{5,2}\alpha_2 + \cdots C_{5,K}\alpha_K + D_5$

. = ….

$W_{4N-3} = C_{4N-3,1}\alpha_1 + C_{4N-3,2}\alpha_2 + \cdots C_{4N-3,K}\alpha_K + D_{4N-3} \ldots\ldots\ldots\ldots..(12)$

Where $C_{1,1}, C_{1,2}, \ldots C_{4N-3,K}$ are the coefficients of the switching angles & $D_1, D_5, \ldots D_{4N-3}$ are constants. The matrix form of eq. (12) is

$$\begin{bmatrix} W_1 \\ W_5 \\ . \\ W_{4N-3} \end{bmatrix} = \begin{bmatrix} C_{1,1} & C_{1,2} & C_{1,3} \ldots . C_{1,K} \\ C_{5,1} & C_{5,2} & C_{5,3} \ldots . C_{5,K} \\ \ldots & & \\ C_{4N-3,1} & & C_{4N-3,2} \ldots . C_{4N-3,K} \end{bmatrix} \times \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ . \\ \alpha_K \end{bmatrix} + \begin{bmatrix} D_1 \\ D_5 \\ . \\ D_{4N-3} \end{bmatrix} \ldots ..(13)$$

From eq. (8) & eq. (13)

$$\begin{aligned} [A] &= [B][C][\alpha] + [B][D] \\ &= [E][\alpha] + [F] \end{aligned} \qquad \ldots\ldots\ldots\ldots(14)$$

Using K switching angles per quarter period, the degree of freedom in eq. (14) is K. It is desirable to use one degree of freedom to control the fundamental amplitude, & $(K-1)$ degrees of freedom are used to eliminate the $(K-1)$ unwanted harmonics. By setting the selected $(K-1)$ harmonic amplitudes equal to zero, eq. (14) becomes:

$A_1 = E_{1,1}\alpha_1 + E_{1,2}\alpha_2 + E_{1,3}\alpha_3 + \cdots E_{1,K}\alpha_K + F_1$

$0 = E_{2,1}\alpha_1 + E_{2,2}\alpha_2 + E_{2,3}\alpha_3 + \cdots E_{2,K}\alpha_K + F_2$

. .

. .

$0 = E_{K,1}\alpha_1 + E_{K,2}\alpha_2 + E_{K,3}\alpha_3 + \cdots E_{K,K}\alpha_K + F_K \ldots\ldots\ldots\ldots\ldots\ldots\ldots . \ldots . (15)$

Eq. (15) can be used to analyze a quarter period of the PWM waveform. By initializing the switching angles α_k in the m_k sampling interval, the E & F can be computed & eq. (15) is solved to compute the switching angles corresponding to the desired fundamental amplitudes under the constraints of the initial conditions **[6]**. The switching angles are determined for the three phases of 5-level, 9-level, 17-level, 33-level, 65-level CMLI using Walsh function method & MATLAB package is employed. The values of switching angles in the first quarter period for output voltage waveforms are shown in **table (1- a, b, c, d, & e). Figure. (2)** shows the relationship between switching angles & the number of output voltage levels (m), the higher number of switching angles because increased in the number of output voltage levels, this means that the improved quality of output voltage waveform with smaller output voltage steps which result in lower harmonic components & better efficiency of the three phase CMLI system.

Table (1-a) the switching angles (in degrees) of 5-level CMLI

Number of sources (N=2) Fundamental amplitude (A_1=1.0 p.u.)	
α_1 (^{O})	26.0297
α_2 (^{O})	55.5822

Table (1-b) the switching angles (in degrees) of 9-level CMLI

Number of sources (N=4) Fundamental amplitude (A_1=1.0 p.u.)	
α_1 (^{O})	16.1274
α_2 (^{O})	30.7695
α_3 (^{O})	47.6676
α_4 (^{O})	77.6589

Table (1-c) the switching angles (in degrees)of 17-level CMLI

Number of sources (N=8) Fundamental amplitude (A_1=1.0 p.u.)	
α_1 (^{O})	10.5500
α_2 (^{O})	19.9488
α_3 (^{O})	28.0255
α_4 (^{O})	39.3157
α_5 (^{O})	49.2814
α_6 (^{O})	58.0777
α_7 (^{O})	69.3785
α_8 (^{O})	79.0168

Table (1-d) the switching angles (in degrees)of 33-level CMLI

Number of sources (N=16) Fundamental amplitude (A_1=1.0 p.u.)	
α_1 (^{O})	5.1095
α_2 (^{O})	11.5105
α_3 (^{O})	16.4139
α_4 (^{O})	21.8234
α_5 (^{O})	26.4824
α_6 (^{O})	31.5510
α_7 (^{O})	36.0903
α_8 (^{O})	41.0945
α_9 (^{O})	47.4967
α_{10} (^{O})	52.6744
α_{11} (^{O})	57.0919
α_{12} (^{O})	63.4220
α_{13} (^{O})	68.8688
α_{14} (^{O})	74.3083
α_{15} (^{O})	79.6958
α_{16} (^{O})	87.7546

Table (1-e) the switching angles (in degrees)of 65-level CMLI

Number of sources (N=32) Fundamental amplitude (A_1=1.0 p.u.)	
α_1 (^{o})	3.8204
α_2 (^{o})	6.3015
α_3 (^{o})	9.1458
α_4 (^{o})	11.8532
α_5 (^{o})	14.5764
α_6 (^{o})	17.1123
α_7 (^{o})	19.8596
α_8 (^{o})	22.6154
α_9 (^{o})	25.3311
α_{10} (^{o})	27.8669
α_{11} (^{o})	30.5719
α_{12} (^{o})	33.4417
α_{13} (^{o})	35.0759
α_{14} (^{o})	38.7095
α_{15} (^{o})	41.4926
α_{16} (^{o})	44.2155
α_{17} (^{o})	46.9183
α_{18} (^{o})	49.6439
α_{19} (^{o})	52.3611
α_{20} (^{o})	54.0937
α_{21} (^{o})	57.8241
α_{22} (^{o})	60.565
α_{23} (^{o})	63.2093
α_{24} (^{o})	65.0619
α_{25} (^{o})	68.8182
α_{26} (^{o})	71.5825
α_{27} (^{o})	74.3510
α_{28} (^{o})	77.1288
α_{29} (^{o})	79.9118
α_{30} (^{o})	82.6015
α_{31} (^{o})	85.4981
α_{32} (^{o})	88.2011

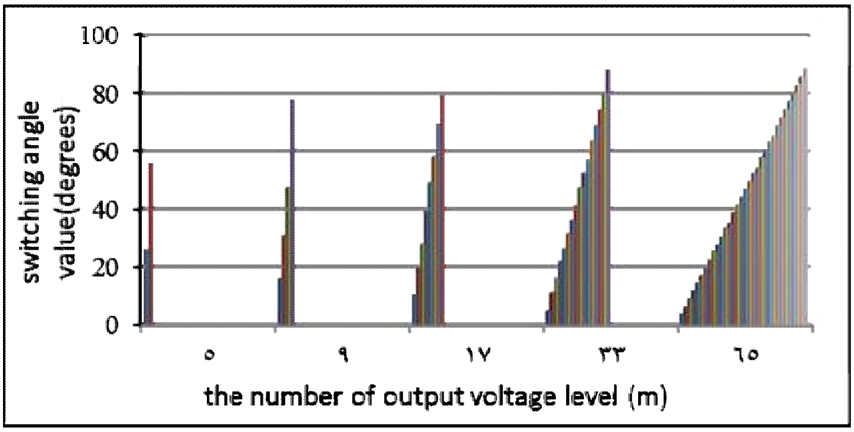


Fig. (2) Switching angles as a function of the number of output voltage level with fundamental amplitude (A_1=1.0p.u.) for three phase CMLI

4- Simulation results

To design a simulation system for three phase CMLI with separate dc sources (batteries) & used to drive an induction motor , ORCAD program is employed as a simulation tool. A piecewise linear (PWL) voltage sources is used to represent a full bridge CMLI. The schematic of three phases 9-level CMLI is illustrated in **Figure. (3)** , the four PWL voltage sources are used to generate (192V_{peak} - 400Hz) output phase voltage. Thus, the total number of PWL for three phase system is (12). A resistor (10Ω) & an inductor (2.5 mH), which connected in series, is used as the load per phase (motor) in the CMLI circuit.

The simulation results of phase , line output voltage &load current waveforms with different number of output voltage levels for three phase CMLI were measured & are shown in **Figure.(4)** .This means that an increasing of the number of output voltage levels will causes that the output waveform much closer to sinusoidal waveforms.

The frequency spectrum of phase , line output voltage & load current waveforms for three phase 9-level CMLI (eliminating 3 harmonics with orders 5th, 7th, 11th) as shown in **Figure.(5)** , this is very practical to eliminate the harmonic up to the (11th) & the (13th) harmonic is the lowest harmonic component appearing in the line output voltage waveform .For three phase 17-level CMLI (eliminating 7 harmonics with orders 5th, 7th, 11th, 13th,…,23th), this is eliminate the harmonic up to the (23th), the (25th) harmonic is the lowest harmonic component appearing in the line output voltage waveform, for three phase33-level CMLI (eliminating 15 harmonics with orders 5th,7th,11th,…..47th) , this is eliminate the harmonic up to the (47th), the(49th) harmonic is the lowest harmonic component appearing in the line output voltage waveform & for three phase 65-level CMLI(eliminating 31 harmonics with orders 5th,7th,11th,….,95th), this is eliminate the harmonic up to the (95th) , the (97th) harmonic is the lowest harmonic component appearing in the line output voltage waveform .This means that the advantage of three phase system is that all triplen harmonic components in the line output voltage will be eliminated by one –third cycle phase shift feature. Therefore only non-triplen harmonic component need to be eliminated from phase output voltage .Therefore, an increasing number of output voltage levels will result increase in number of low order eliminated harmonics, which causes to push more harmonic energy into high frequency regions, therefore low frequency harmonics are will attenuated.

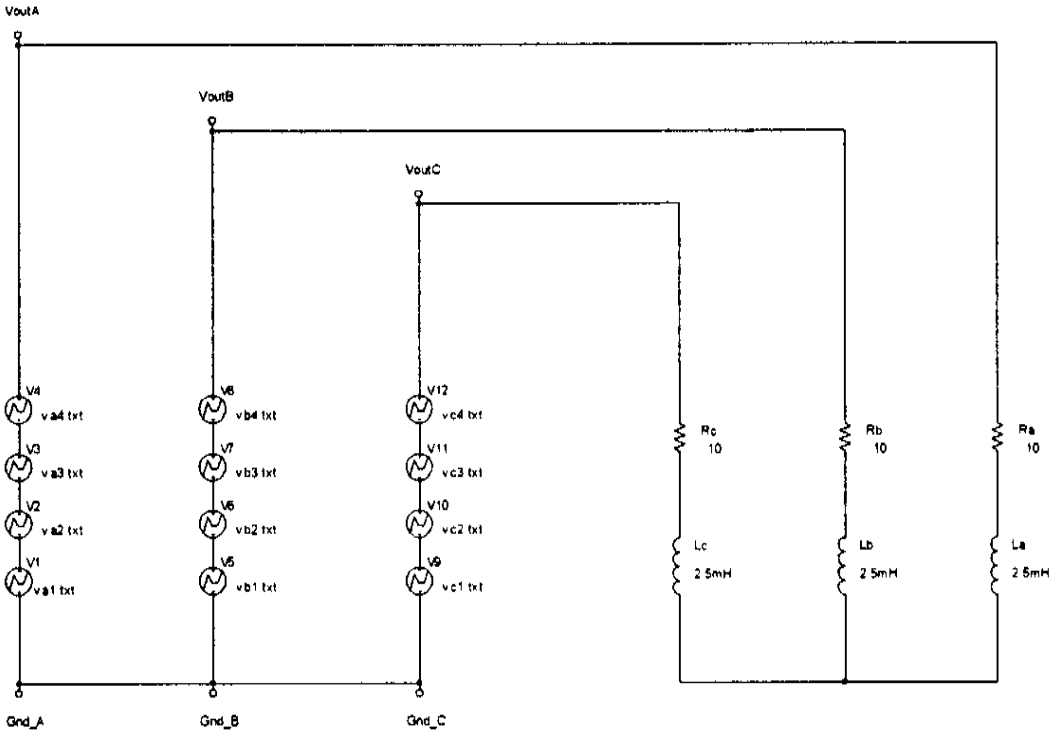
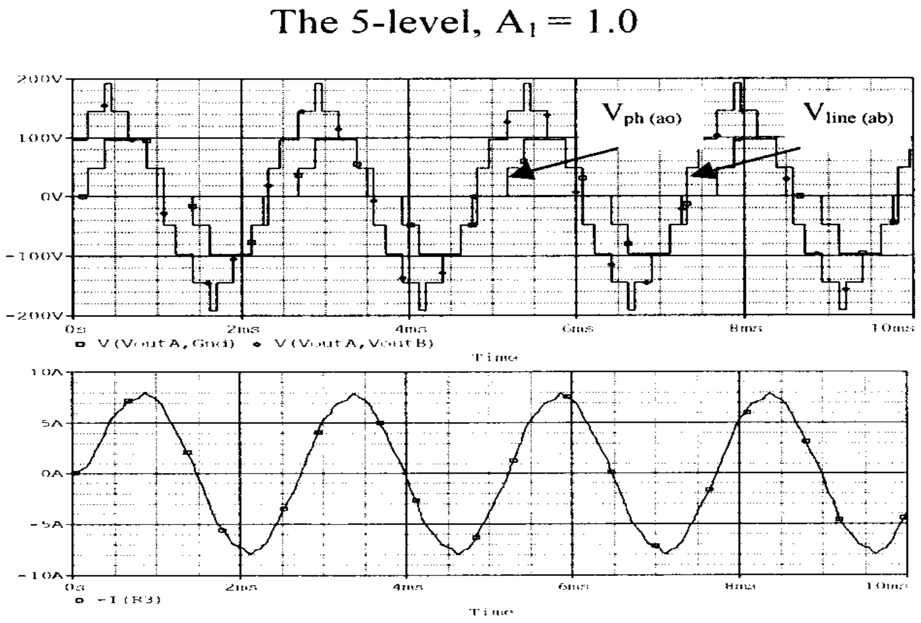
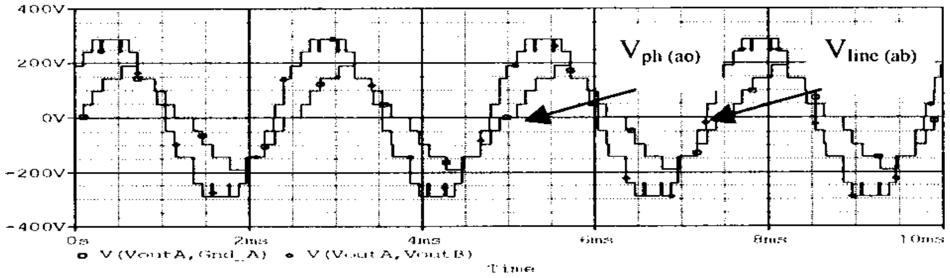
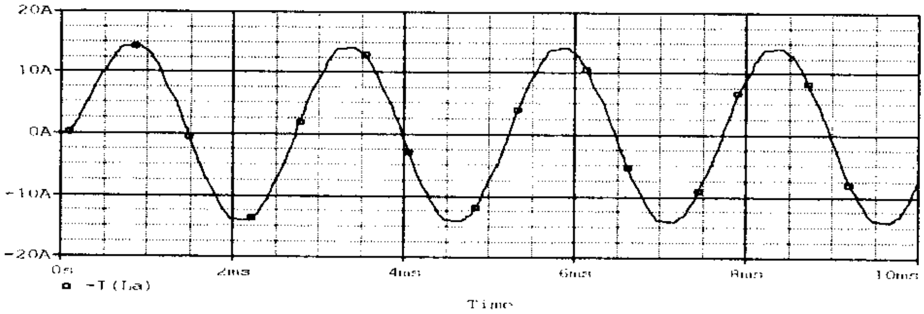


Fig. (3) A schematic of a three phase 9-level CMLI

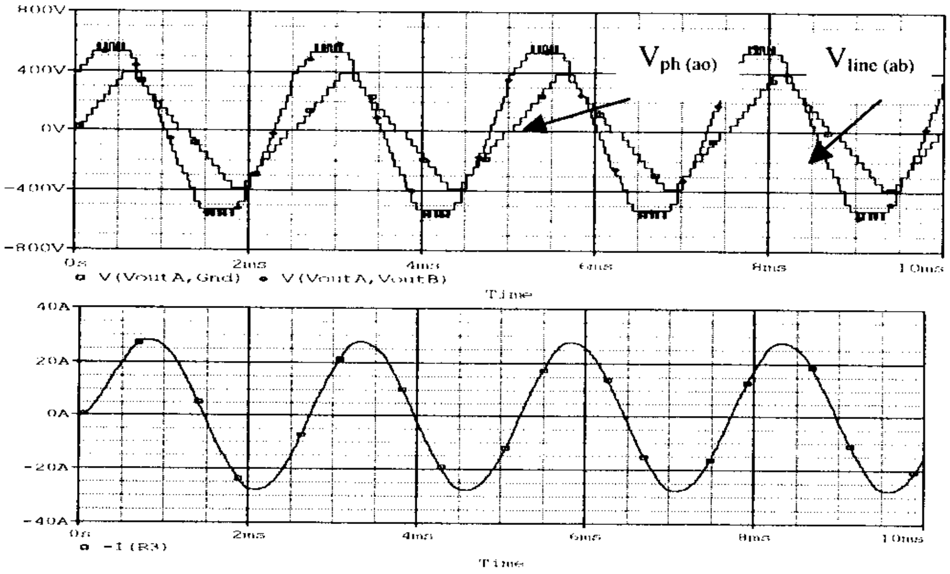


The 9-level, $A_1 = 1.0$

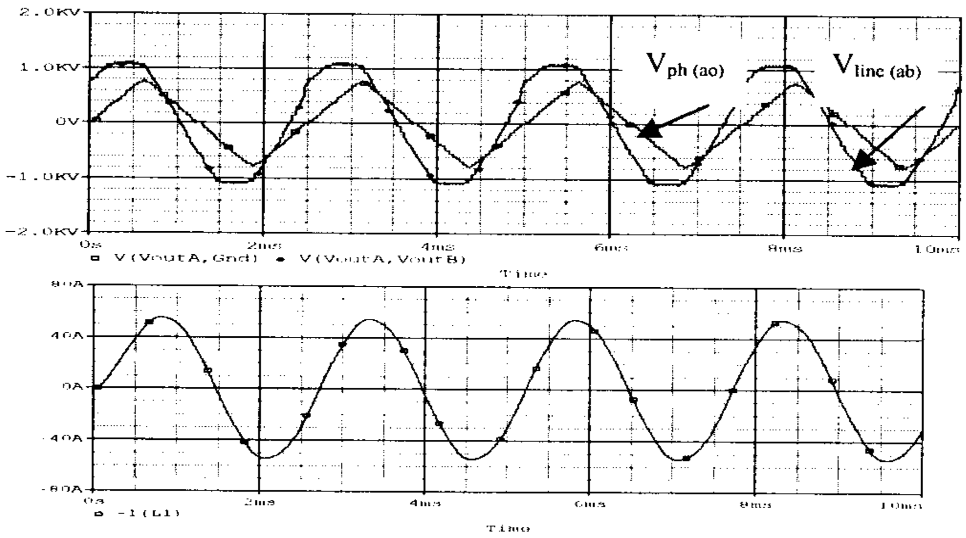




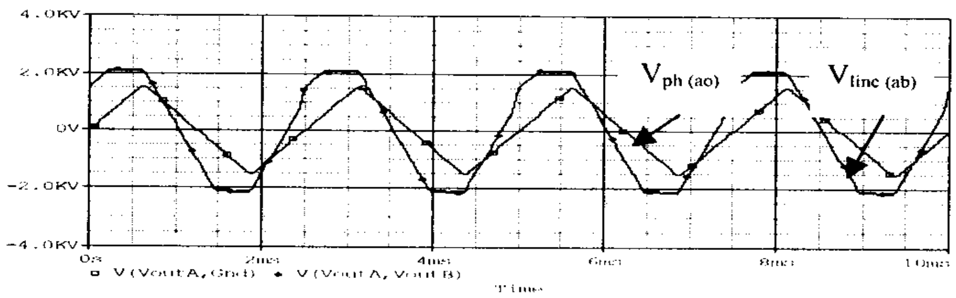
The 17-level, $A_1 = 1.0$



The 33-level, $A_1 = 1.0$



The 65-level, $A_1 = 1.0$



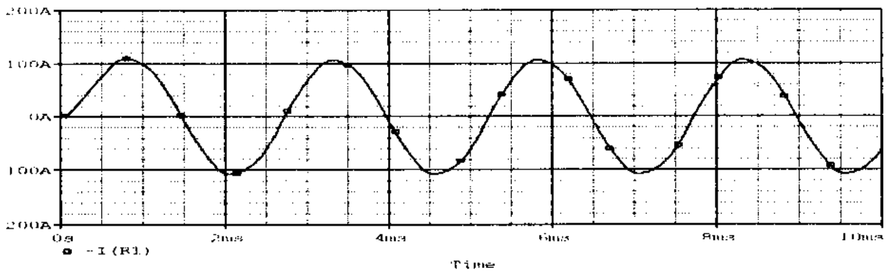


Fig. (4) Phase, line voltage &load current waveforms of three phase 5-level, 9-level, 17-level, 33-level, 65-level CMLI with fundamental amplitude (A_1=1.0p.u.)

The 9-level, $A_1 = 1.0$

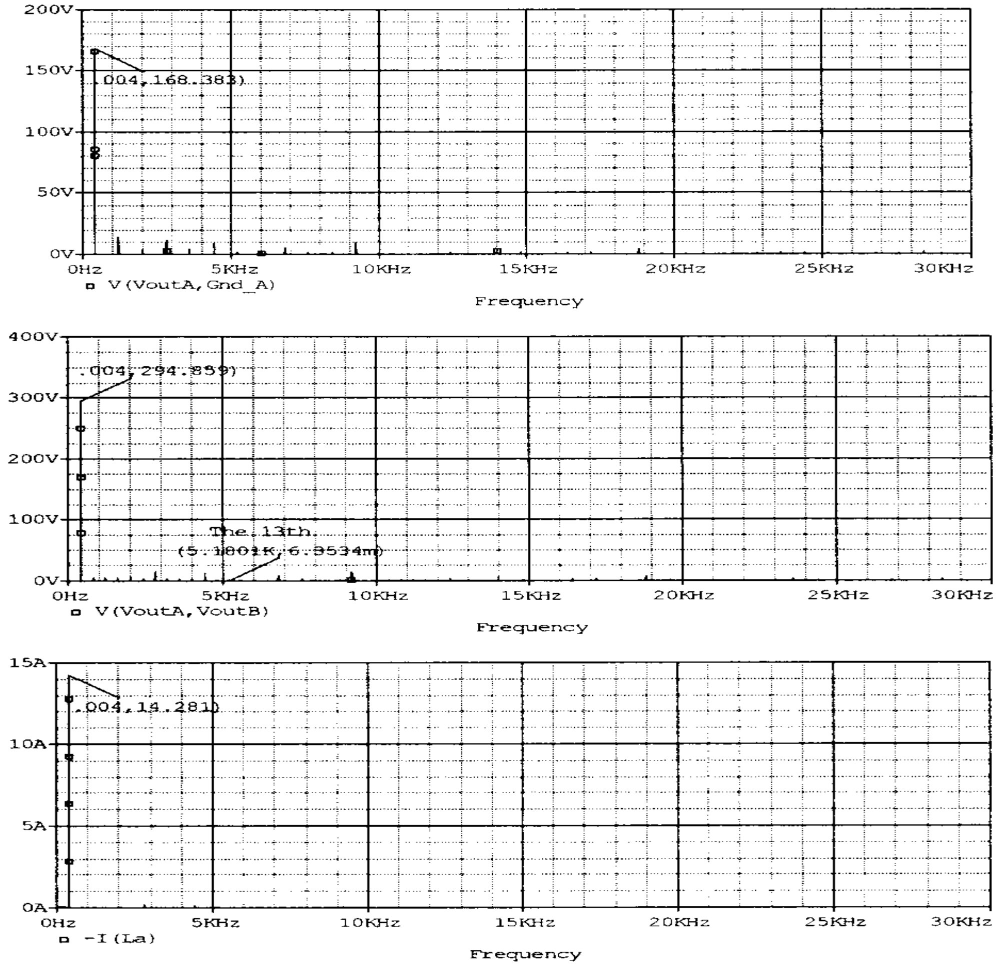


Fig.(5) Frequency spectrum of phase ,line voltage &load current in detail of three phase 9-level CMLI with fundamental amolitude (A_1=0p.u.)

5- Evaluation of harmonic elimination PWM technique for three phase CMLI

There are four performances used in this paper to evaluation the harmonic elimination PWM technique for three phases CMLI defined as follows:

Harmonic factor (HF): the harmonic factor (of the nth harmonic), which is a measure of individual harmonic contribution, is defined as

$$HF_n = \sqrt{[(V_n/V_1)^2 - 1]} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

Where: V_1 fundamental voltage (rms).

V_n harmonic voltage (rms)

n order of harmonics.

Harmonic loss factor (HLF): the harmonic loss factor, which is proportional to total rms harmonic current, is defined as:

$$HLF = (1/V_1)\sqrt{\sum_{n=5}^{n=125} [V_n/n]^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (17)$$

Total harmonic distortion factor (THD): the total harmonic, which is a measure of closeness in shape between a waveform & its fundamental voltage, is defined as:

$$THD = (1/V_1)\sqrt{\sum_{n=5}^{n=125} (V_n)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (18)$$

Distortion factor (DF): the distortion factor indicates the amount of harmonic distortion that remains in a particular waveform after the harmonics of that waveform have been subjected to a second- order attenuation (i.e., divided by n^2). Thus DF is a measure of effectiveness in reducing unwanted harmonics without having to specify the values of a second-order load filter & is defined as:

$$DF = (1/V_1)\sqrt{\sum_{n=5}^{n=125} [V_n/n^2]^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . . (19)[7].$$

Evaluation of the three phase CMLI performance with the proposed technique can be calculated from the performance factors (HF, HLF, DF, THD) in eq. (16, 17, 18, 19) as shown in **Table (2).** The performance factor versus the number of bridge inverter per phase (N) for fundamental amplitude (A_1=1.0) are shown in **Figure. (6)** at , illustrates the relationship between these factors & N .We can see that increasing N causes decreasing these performance factors .Notice that ,the motor will behave just like motor supplied directly by sinusoidal power supply, so that the motor will be more quit with higher N.

By comparing this proposed technique with the previous work in [8] that use Newton Raphson (N-R) method based on nonlinear transcendental equations for switching angles & the system is single phase. We can see that the output voltage THD was reported to be (8.08%) for a single phase 9-level CMLI, while this paper proposed the output line voltage THD is (5.59%) for three phase 9-level CMLI, that significantly reduced to (3%) decimal places & overall THD% is reduced.

The voltage fundamental component spectra of three phases CMLI are given in figures. (7, 8) with the number of output voltage levels (m). It can be see that the value of fundamental component amplitude of line voltage waveform increases their phase voltage with increasing the number of output voltage levels. Therefore, using the multilevel fundamental switching scheme will result in the better output voltage quality & increased efficiency.

The system of three phase CMLI has very high efficiency of (98%) as shown in **Figure.(9),** because the proposed switching angle technique can provide a more sinusoidal output voltage waveform as compared with the previous work in [9], that use to a single phase traditional 2- level PWM inverter.

Table (2) The value of performance factors (HF, HLF, DF,THD) of three phase CMLI

A_1=1.0	N=2	N=4	N=8	N=16	N=32
HF%	**51.8438**	**18.3426**	**9.9730**	**9.6897**	**7.2840**
HLF%	**3.0672**	**1.4099**	**1.1081**	**0.8567**	**0.6940**
DF%	**0.3552**	**0.2305**	**0.1455**	**0.1020**	**0.0531**
THD%	**13.6259**	**5.5974**	**2.6543**	**1.0164**	**0.9651**

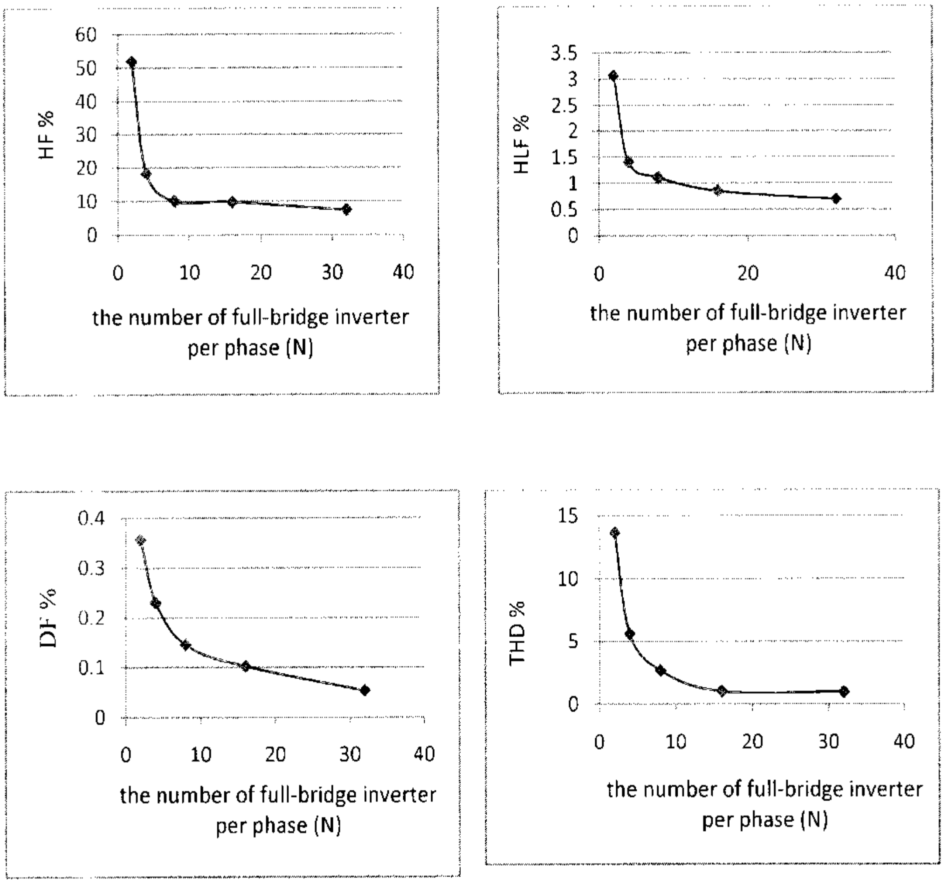


Fig (6) Performance factors as a function of the number of bridge (N) with fundamental amplitude (A_1=1.0p.u.) for three phase CMLI

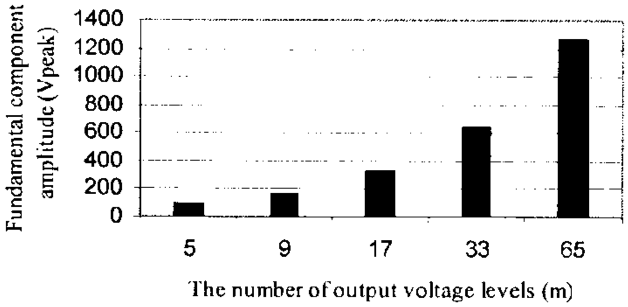


Fig. (7) Fundamental component amplitude (V_{peak}) of phase voltage as function of the number of output voltage levels (m) for three phase CMLI

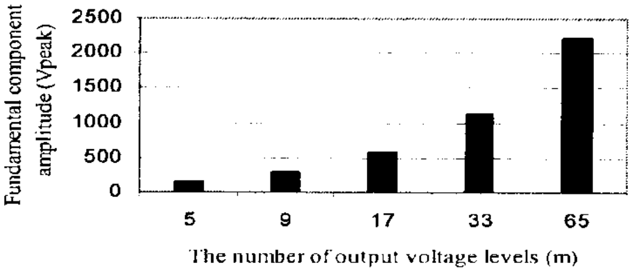


Fig. (8) Fundamental component amplitude (V_{peak}) of line voltage as function of the number of output voltage levels (m) for three phase CMLI

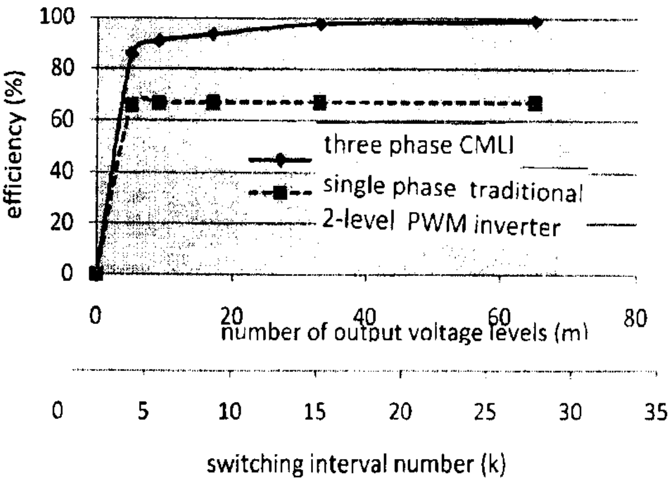


Fig.(9) System efficiency (three phase CMLI) as a function of the number of output voltage level (m)

6- Conclusion

1. The proposed technique superior over the traditional PWM by using (N-R) method to completely eliminates any number of harmonics to get highest quality motor drive with very low distortion waveform.
2. The increase in the number of output voltage levels in MLI result in a better approximation to a sinusoidal waveform. Furthermore the increased number of output voltage levels provides the opportunity to eliminate more harmonic content. Then, we find that there is no needed to use any filtering components.
3. Increasing of number of output voltage levels in MLI upper from 65 levels causes increase of THD & decrease in fundamental component amplitude of output voltage waveform then lowest quality motor drive with very high distortion waveform.
4. The performance factors (HF, HLF, DF, & THD) for output voltage waveform is reduced & staircase voltage waveform is obtained which much closer to sinusoidal waveform.
5. The best compromise between high efficiency & high quality of the three phase CMLI operation is achieved by the proposed technique.

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