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Harmonics Study of 3-Phase Space Vector PWM Inverter

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Abstract

This paper proposes the modeling ,implementation and simulation of three phase induction motor driver, using voltage- fed space vector pulse width modulation technique (SVPWM).The sources of total harmonics (i.e. total effective harmonics,inter-harmonics,and sub-harmonics) and how it affects on drive system and their affects on the supply power network are studied.

A developed formula of total harmonics distortion factor (THD) including ,inter -harmonic, and sub- harmonic has been introduced while in the previous studies are neglected.

The effect of inter-harmonics and sub-harmonics on the performance parameter of total harmonics distortion factor , switching losses factor (SLF) and quality factor (QF) has been deduced.

Modeling , and simulation of the system using PSIM software are also presented.

All results are obtained by studying the waveforms of voltage and current at the source and load sides with different speeds of motor drive.

The simulation and experimental result are consistent with theoretical studies and excellent , they indicate that the model is accurate and practicable.

Keywords: Harmonics,Inter-and Sub-harmonics,SVPWM, inverter,Induction Motor .

دراسةالتوافقيات لمضمن عرض النبضة ثلاثي الطور ذو المتجه الفضائي

الخلاصة

يقدم هذا البحث تمثيل وتطبيق مسوق قدرة لمحرك حثي ثلاثي الطور باستخدام مغذي جهد بتقنية تضمين عرض النبضة للمتجه الفضائي .

مصادر التوافقيات الكلية (التوافقيات الفعالة الكلية ، التوافقيات الداخلية و التوافقيات الثانويه وتأثيرها على الجهازالمقدم والمحرك و على شبكات تجهيز القدرة .كما تم اقتراح صيغة عامل التشويه للتوافقيات الكلية بتضمينها التوافقيات الداخلية والجانبية .

تم استنتاج تأثير التوافقيات الداخلية والتوافقيات الجانبية على أداء العلاقات المتعلقة بعامل التشويه الكلي للتوافقيات ، عامل خسائر التحويل وعامل النوعية .

تم تقديم النموذج والتطبيق والتمثيل للنظام باستعمال برنامج (PSIM) .

كل النتائج قد استخرجت بدراسة موجات الفولتية والتيار في جهة المصدر وفي جهة الحمل مع مختلف السرع لمسوق المحرك.

ومن خلال نتائج الاختبار العملي والتمثيل الرياضي ومقارنتها مع الدراسات النظرية تبين على انها بتوافق دقيق وعملي .

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1. Introduction

SVPWM method is an advanced, Computation-intensive PWM method is possibly the best among all the PWM techniques for voltage source inverter, its advantage like good dc utilization and less harmonics distortion in the output waveform, it has been finding widespread application in recent years [1,2].

SVPWM contain two sides, the source side consist of (dc- link) rectifier and the other side define as a load side consist of voltage source inverter feeding induction motor as show in Figure (1).The two sides generate a wide spectrum of harmonic components (effective;Harmonics,Inter-harmonics and Sub- harmonics) which deteriorate the quality of the delivered energy and increase the energy losses as well as decrease the reliability. The other mainly disadvantage in the form of short picks and spikes, can cause malfunctioning or even braking down of power electronic equipment. So harmonics are one of the major power and system quality concern. The behavior and performance study of SVPWM drive induction motor related to harmonic effect is based on effetive harmonics only which is measured in the supply and load side voltage. While the inter-harmonics and sub- harmonics are neglected in previous searchs.In this paper total harmonics distortion factor (THD) including inter-harmonics, and sub- harmonics has been introduced with whole drive system [3, 4, 5].

There are three components of spectrum, which can be classified as follows:

(i)Harmonics whose frequencies are integer multiples of fundamental frequency, called effective harmonics,

(ii)Harmonics whose frequencies are non-integer multiples of fundamental frequency, called inter- harmonics and

(iii)Harmonics whose frequencies are below the fundamental frequency, referred to as sub- harmonics.

2.1nter-harmonicsandSub-armonics

According to Fourier theory, a predict waveform can be expressed as a sum of pure sine wave of different amplitude were the frequency of each sinusoid is an integer multiply of fundamental frequency of waveform . A frequency that is an integer multiply of fundamental frequency called harmonic frequency i.e f_h=hfi where f_1 and h are the fundamental frequency and integer number respectively .

The following equation provides a simple effective mathematical definition:

Dc f= 0Hz (f=h*f, where h=0) …. (1)

Harmonic f= h*f_1 … (2)

Inter-harmonic f # h*f … (3)

Sub-harmonic f > 0Hz and f<f_1.. (4)

There are two basic mechanisms for the sources and generation of inter &sub

harmonics. The first is the generation of components in the sidebands of the supply voltage frequency and its harmonics as a result of changes in their magnitudes and/or phase angles. These are caused by rapid changes of current in equipment and installations, which can also be a source of voltage fluctuations Disturbances are generated by loads operating in a transient state, either continuously or temporarily, or, in many more cases, when an amplitude modulation of currents and voltages occurs. These disturbances are of largely random nature, depending on the load changes inherent in the processes and equipment in use. The second mechanism is the asynchronous switching (i.e. not synchronized with the power system frequency) of semiconductor devices in SVPWM drive [6, 7].

3. Harmonics calculation

3.1Traditional (THD) Factor

It is the ratio of the root mean square of the harmonic content to the root mean square value of the fundamental quantity, expressed as a percentage of the fundamental [2] . When the value of current have a harmonic the THD classify in two type:

a. Current Total Harmonic Distortion:

$$\mathrm{THD_I} = \sqrt{\sum_{K=2}^{\infty}(I_{krms}^2)}\ /I_{1rms} * 100\%) \quad ....(5)$$

Where:

I_{krms} = rms value of the total effective harmonics component, (for current)

I_{1rms} = rms value of the fundamental component. (for current)

K = running number of the total effective harmonic component (for current).

B.Voltagetotalharmonic Stortion

$$\mathrm{THD_V} = \sqrt{\sum_{K=2}^{\infty} V_{krms}^2}\ /V_{1rms} * 100\% \quad \ldots (6)$$

Where:

V_{krms} = rms value of the total effective harmonic component for voltage.

V_{1rms} = value of the fundamental component for voltage

K = running number of the total effective component for voltage.

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3.2TotalInter-harmonicsDistortion Factor (TIHD)

It is the ratio of the root mean square of inter harmonic component to the root mean square value of the fundamental quantity [8, 9].

$$\mathrm{TIHD} = \sqrt{\sum_{i=1}^{n} Q_i^2}\ /Q_1 . \quad \ldots (7)$$

Where:

Q_1 = rms value of the fundamental component

Q_i = rms value of the inter-harmonics

i = running number of inter-harmonics

n = total number of considered inter -harmonics

the Q_i every point harmonic in the signal spectrum after the fundamental except the total effective harmonic component .but this make the measure more complex so we take the magnitude of (Q_i) every (5HZ). $TIHD$ classify into two terms:

1-$TIHD_V$ Voltage total inter-harmonics distortion factor.

2-$TIHD_I$ Current total inter harmonic distortion factor .

3.3 Total Sub- harmonic Distortion factor (TSHD)

It is the ratio of the root mean square of the sub harmonic component to the root mean square value of the fundamental quantity [10].

$$\text{TSHD} = \sqrt{\sum_{j=1}^{s} C_i^2} / Q_1 \quad .. \quad (8)$$

Where:

Q_1 = rms value of the fundamental component

C_i = rms value of the sub-harmonics

j = running number of sub-harmonics

S = total number of considered sub-harmonics

When (C_i) the spectral component of sub-harmonics group of harmonics before the fundamental.

TSHD classify into two terms:

1- $TSHD_V$ Voltage Total Sub-harmonics Distortion Factor.

2- $TSHD_I$ Current Total Sub-harmonics Distortion Factor.

3.4 Calcaulation of Total Harmonic (THDT

It is mean the summation of all effect of the effective harmonic component, inter-harmonics and sub-harmonics and express as shown below:

THDT=TIHD+TSHD+THD**….** (9)

The (THDT) is very useful to know the true effect of harmonic distortion on the signal (i.e current or voltage waveforms) for the source side and the load side . The quality of network power and the optimization of the drive system are also related.THDT classify into two term:

1- $THDT_V$: summation of total harmonics for voltage.

2-$THDT_I$: summation of total harmonics for current.

4. Switching Losses Factor (SLF) & The Quality Factor (QF)

$$\text{SLF} = \sum_{j=1}^{p} i_{a.j}^2 \ldots\ldots \quad (10)$$

Where:

i_a =The instantaneous value of inverter current.

j = the order of switching instant of inverter current at each (P).

P = Number of pulses of total effective harmonics component.

$$\text{QF} = 100 \frac{M^2}{SLF \times THDT_{I\%}} \quad \ldots. \quad (11)$$

These values are very important to know the quality of output inverter current at different modulation index (M),especially when the harmonics, inter-harmonics and sub-harmonics are included in signal current as in this work(using $THDT_I$) [11,12].

5. Proposed Model

The space vector pulse width modulation (SVPWM) inverter fed three-phase induction motor was built in lab. The system design and the implementation have been given in details [13].

The performance analysis and simulation has been established using PSIM program package. PSIM program provides a powerful and efficient environment for power electronics and motor control simulation. PSIM's graphic user interface is intuitive and very easy to use. A circuit can be easily setup and edited. The simulation results can be analyzed easily using various post-processing function in the waveform display program [14].

The blocks and their parameters of modified SVPWM inverter are given in the followings:

1-Space vector calculation, vector location, and time interval calculation blocks. Then;

2-The circuit of voltage source Inverter drive induction motor are shown in fig.2.

In this work the overall system is simulated using developing simulation program (PSIM) . when analysis the signal in the program the steady state time have been taken every 5 Hz. Therefore the waveform analysis become easy[15]

6.SimulationandExperimental Results

The data of parameter values as the following: -

The data of induction motor is 3-phase ,380v ,1100 watt , 2pole, 2800 rpm , 50 Hz, Rs=6Ω, Xs=25.13Ω , Rr=15Ω (referred to stator) , Xr=12.5Ω (referred to stator) , and Xm=300Ω .

The rectifier parameters are C= 880 uF , L= 16 mH and the supply voltage =220v, 50 Hz .

The results at no load operation are performed because the effect of total harmonic distortion THD is higher[7].

Five steps of different modulation indices; 90% , 80% ,70% , 60% and 50% of rated (i.e different voltage and speeds) are taken into calculation to give all possible range of total harmonic analysis and effects.

6.1Current Analysis

The phase motor and input supply current of SVPWM inverter are analyzed using Fourier series . The simulation analysis is done using PSIM program to obtain total harmonics (total effective harmonics ,inter-harmonics,and sub- harmonics) for complete switching frequency (i.e. the switching frequency of real building model which is equal 2KHz).The most important performance current parameters ; $THDT_I$, THD_I , $TIHD_I$, and $TSHD_I$ were obtained for phase and supply current as shown in figures (3),and (4) respectively. Then the quality factor QF and switching losses factor SLF of phase current were also calculated as shown in Figures (5). For more clearness some example results of time and frequency current analysis for modulation index (0.9) of phase and supply currents as shown in Figures (6),and (7) respectively.

The simulation results which were calculated in the above figures are tested experimentally as shown in figures (3/E, 4/E,5/E,6/E,and7/E).

6.1.1 Phase current comparison

By examining the results in Table (1) &fig.5,the following remarks can be recorded :

1- The best value of the quality factor of drive system is that occurs at modulation indices (0.8 ,and 0.9).

2- The quality factor (QF) value determine the quality of inverter current (equation11) . It is value also effect on optimization of drive system .The best quality factor is at 0.9 modulation index , but if the effect of inter-harmonics and sub-harmonics is neglected as in previous studies (i.e the THD_I is only taken) the best value of (QF) is at o.8 modulation index as shown in figures(5 & 5/E).

6.1.2 Supply current comparison

The results of Table (2) leads to the following remarks:

The summation of total harmonics ($THDT_I$) for supply current have been become maximum value at 0.7 modulation index. This is because the two parameter values of inter-harmonics ($TIHD_I$) and sub-harmonics ($TSHD_I$) are also maximum at M=0.7 for the simulation and experimental results therefore the quality of current supply is related to the modulation index value.

6.2Voltage Analysis

Any distortion on the output voltage of inverter from effective harmonic component or inter harmonic and sub harmonic group will be effect on the normal stability operation of the motor and losses. So the analysis of voltage is very important at different operating points. Therefore the performance parameter $THDT_V$,THD_V,$TIHD_V$, $TSHD_V$ as shown in figures [(8) and (8/E)], beside an example of time and frequency analysis of phase voltage also calculated as shown in figures (9) and (9/E),for two cases carried , simulation and experimental respectively.

6.2.1 Voltage Comparison

Table (3) leads to the following remarks:

The summation of total harmonics ($THDT_V$) values increases gradually when modulation index is decreases (i.e the maximum at M=0.5). but the inter-harmonics ($TIHD_V$) and sub-harmonics ($TIHD_V$) values are changed at random manner (i.e the maximum values of ($TIHD_V$) and ($TIHD_V$) at 0.7 and 0.8 modulation index respectively) .

7. Conclusions

A new study of harmonics distortion including inter-harmonics and sub-harmonics has been presented.

The effect of inter-harmonics and sub- harmonics in performance parameter of total harmonic distortion (THDT ,TIHD , and TSHD) , switching losses frequency (SLF) , and the quality factor (QF) have been deduced .

simulation method of SVPWM drive system using PSIM software for study the total harmonics has been developed. .The model enables the researcher to change any parameter of the drive system in the software which can provide convenient for future total harmonics analysis and studies to all type of converter .Therefore the results of simulation and experimental are consistent with theoretical studies, they indicate that the model is accurate and practicable .

Due to simulation and experimental results the following notes are concluded :-

1. The minimum value of ($THDT_I$) of phase current at M = 0.9 .
2. The maximum value of ($TIHD_I$, $TSHD_I$) for phase and supply current at M = 0.7 .
3. The maximum values of ($TIHD_V$, $TSHD_V$) in between M = 0.7 and 0.8.
4. The maximum value of quality factor at M = 0.9 .

The optimum working of the drive system is between modulation index 0.8 and 0.9 .And the effects of inter harmonics and sub-harmonics must be taken in the case of THD calculation.

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Table (1) phase current comparison performance parameter at no load.

M	Simulation results				Experimental results			
	THD_I %	$TIHD_I$ %	$TSHD_I$ %	$THDT_I$ %	THD_I %	$TIHD_I$ %	$TSHD_I$ %	$THDT_I$ %
0.5	186.6	1.7	0.41	188.7	187	2.3	0.55	189.8
0.6	186.2	1.38	0.54	188.1	186	1.9	0.81	188.7
0.7	185.3	14.5	5.7	205.5	184	3.2	6.1	203.3
0.8	186	4	2.1	192.1	187	5.7	3.1	195.8
0.9	184	4.7	1.7	190.4	185	4.2	2.2	191.4

Table (2) supply current comparison performance parameter at no load.

M	Simulation results				Experimental results			
	THD_I %	$TIHD_I$ %	$TSHD_I$ %	$THDT_I$ %	THD_I %	$TIHD_I$ %	$TSHD_I$ %	$THDT_I$ %
0.5	186.6	1.7	0.41	188.7	187	2.3	0.55	189.8
0.6	186.2	1.38	0.54	188.1	186	1.9	0.81	188.7
0.7	185.3	14.5	5.7	205.5	184	3.2	6.1	203.3
0.8	186	4	2.1	192.1	187	5.7	3.1	195.8
0.9	184	4.7	1.7	190.4	185	4.2	2.2	191.4

Table (3) Voltage comparison performance parameter.

M	Simulation results				Experimental results			
	THD_V %	$TIHD_V$ %	$TSHD_V$ %	$THDT_V$ %	THD_V %	$TIHD_V$ %	$TSHD_V$ %	$THDT_V$ %
0.5	100.6	2.7	0.02	103.3	96.2	2.2	0.08	98.48
0.6	80	2.35	0.03	82.35	77.3	1.8	0.1	79.2
0.7	38.7	47	0.37	86.07	35.1	43	0.28	78.3
0.8	29.7	38.7	0.42	68.82	28.4	32.2	0.37	60.9
0.9	36.4	1.6	0.12	38.12	34.2	1.1	0.22	35.52

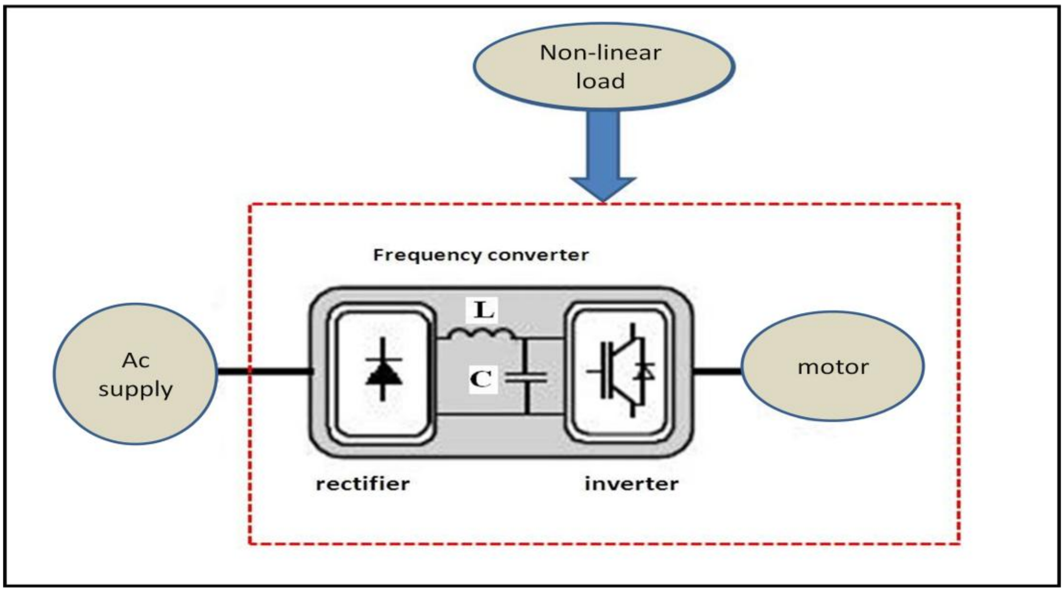

Figure (1) Voltage source inverter with dc-link rectifier side

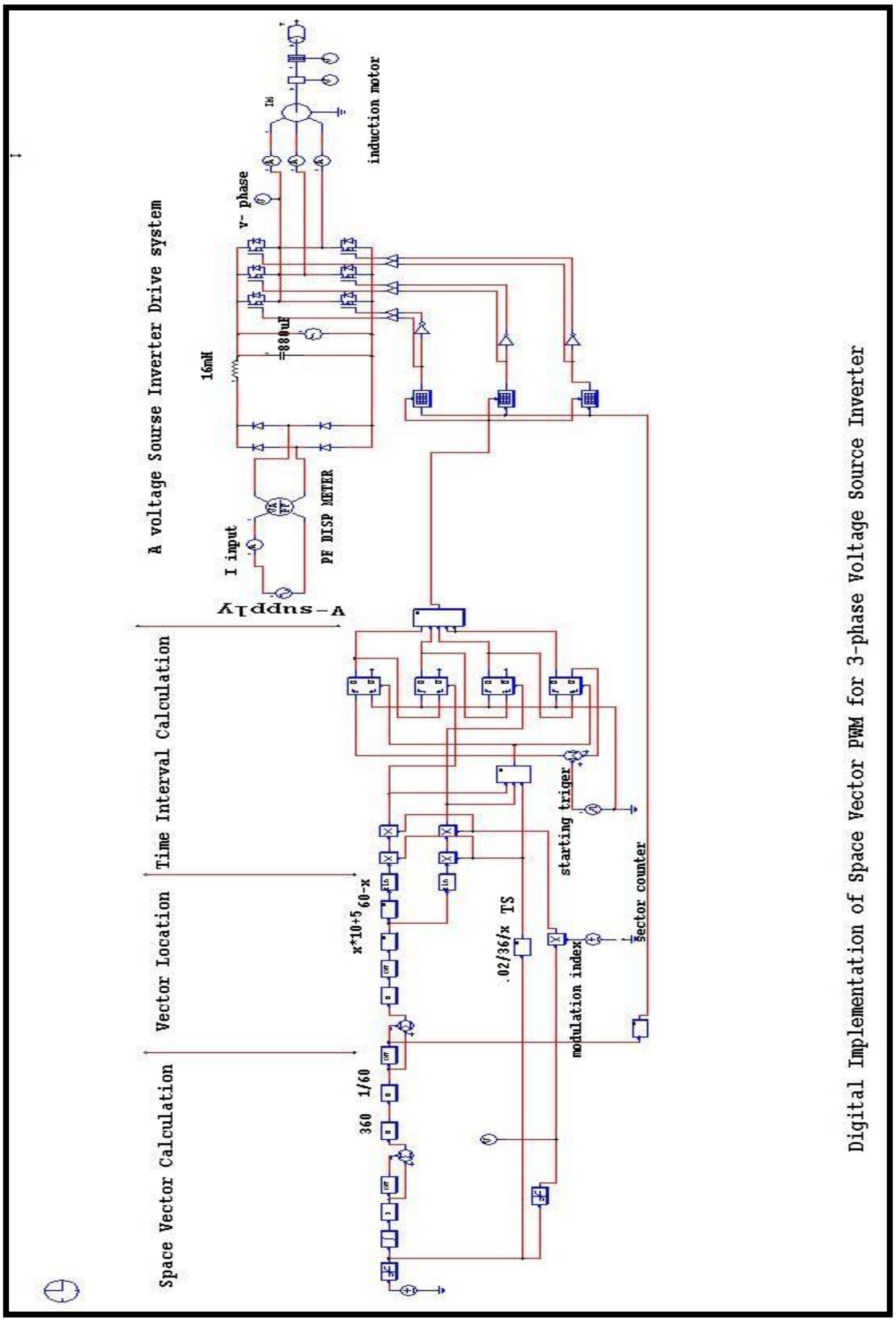

Figure (3) Harmonics amaylsis of phase current at no load
{(a) $THDT_I$ (b) THD_I (c) $TIHD_I$ (d) $TSHD_I$ }

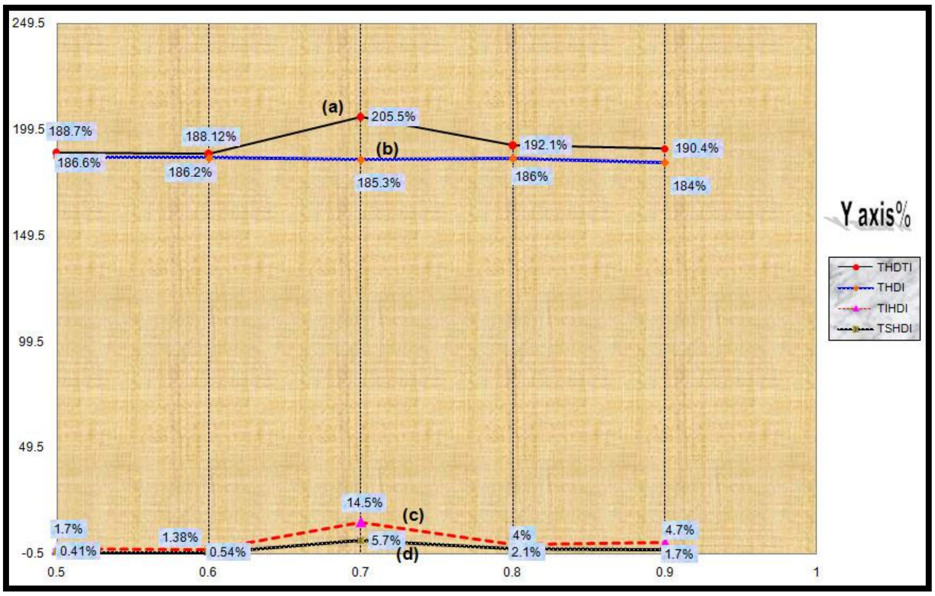

Figure (4) Harmonics analysis of supply current at no- load {(a) $THDT_I$ (b) THD_I(c) $TIHD_I$(d) $TSHD_I$

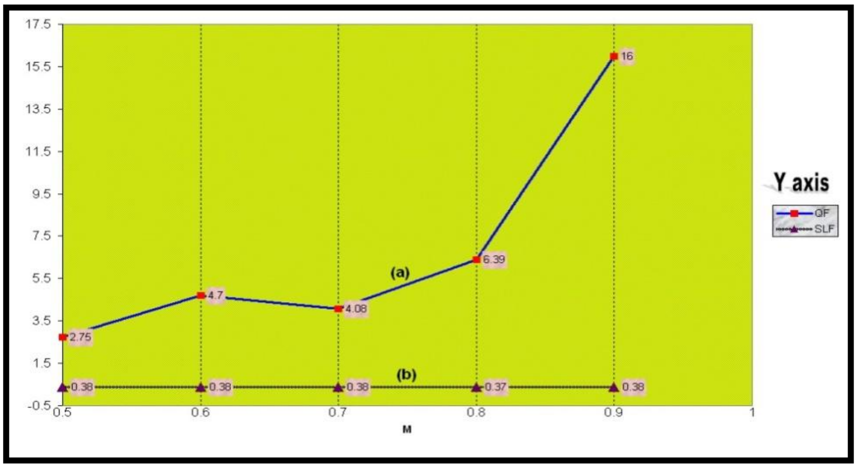

Figure (5) the switching losses factor and quilty factor of motor phase Current at no load {(a) QF (b) SL

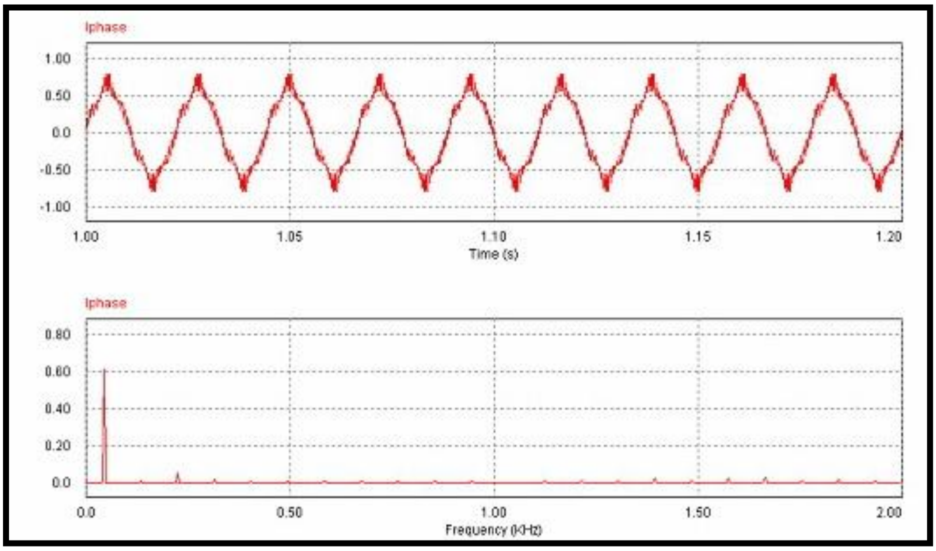

Figure (6) Time and frequency analysis of phase current at no –load at M=0.9

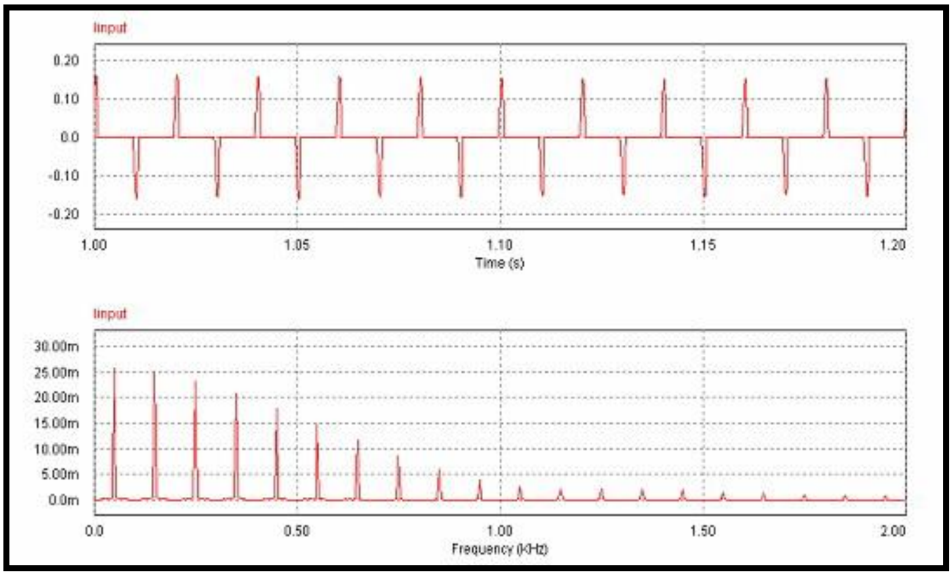

Figure (7) Time and frequency analysis of supply current at no- load at M= 0.9

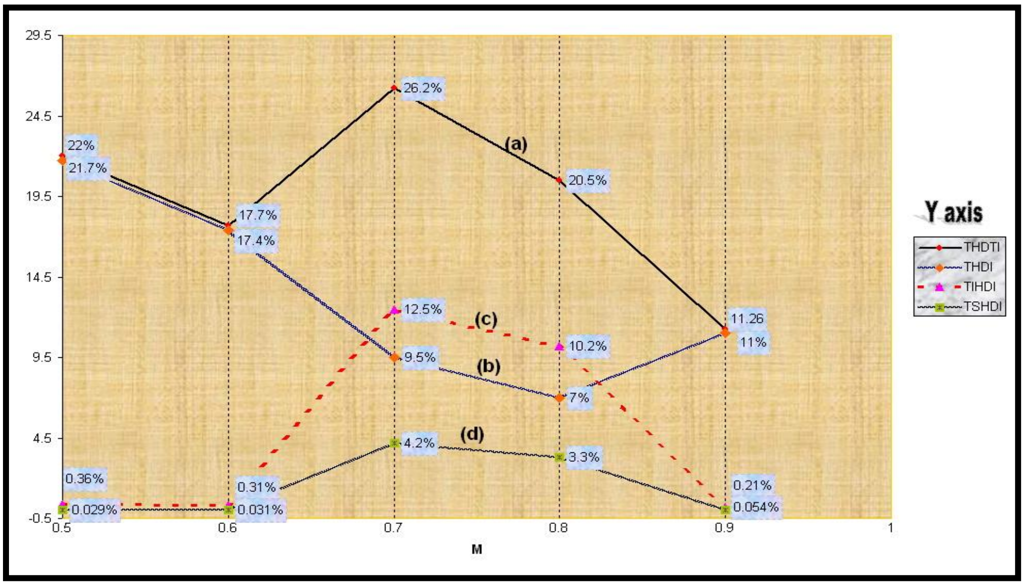

Figure (3/E) Harmonics analysis of phase current at no-load
{ (a) $THDT_I$ (b)THD_I (c)$TIHD_I$ (d) $TSHD_I$ }

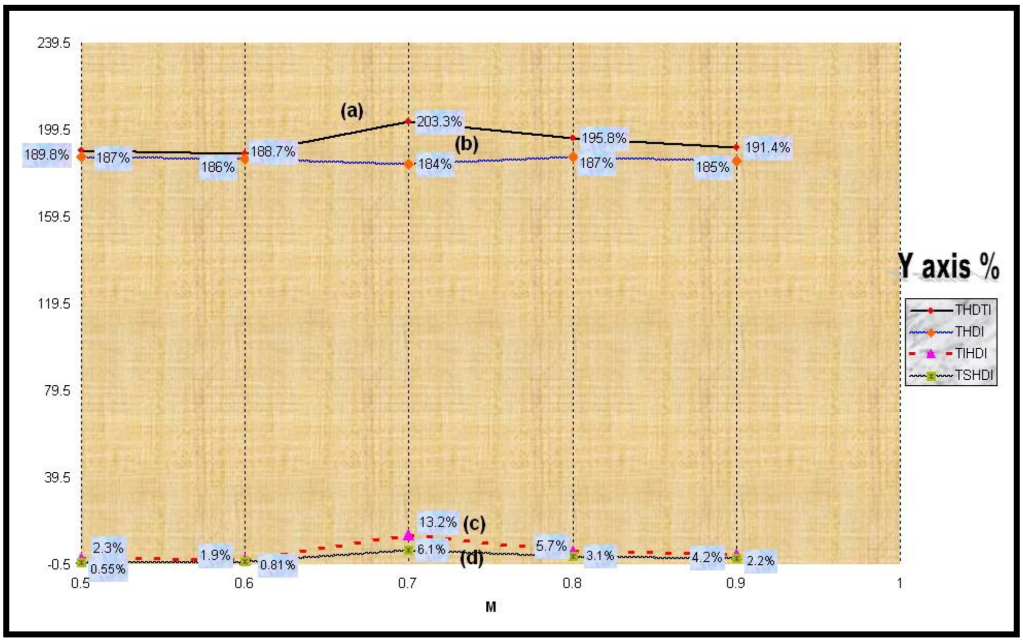

Figure (4/E) Harmonics analysis of supply current at no-load
{ (a) $THDT_I$ (b) THD_I (c) $TIHD_I$ (d) $TSHD_I$}

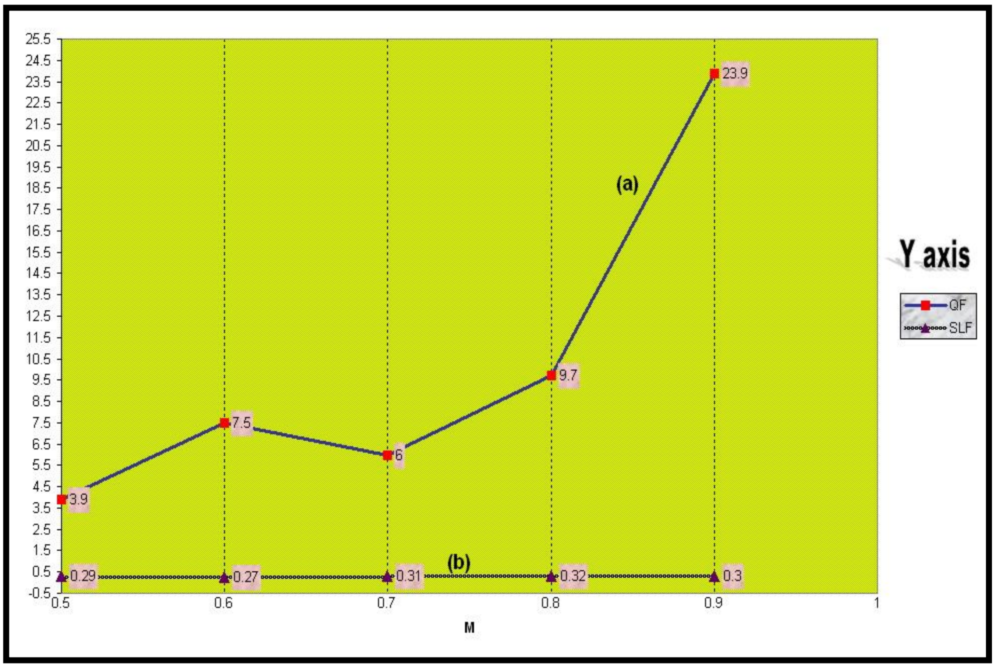

Figure (5/E) The switching losses factor and quilty factor of phase Current at no-load {(a) QF (b) SLF}

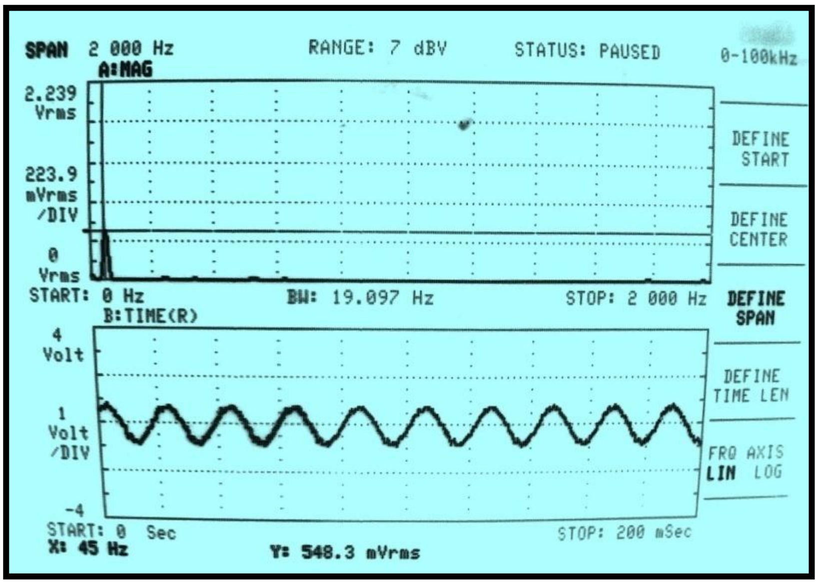

Figure (6/E) Time and frequncy analysis of motor phase current at no-load M =0.9

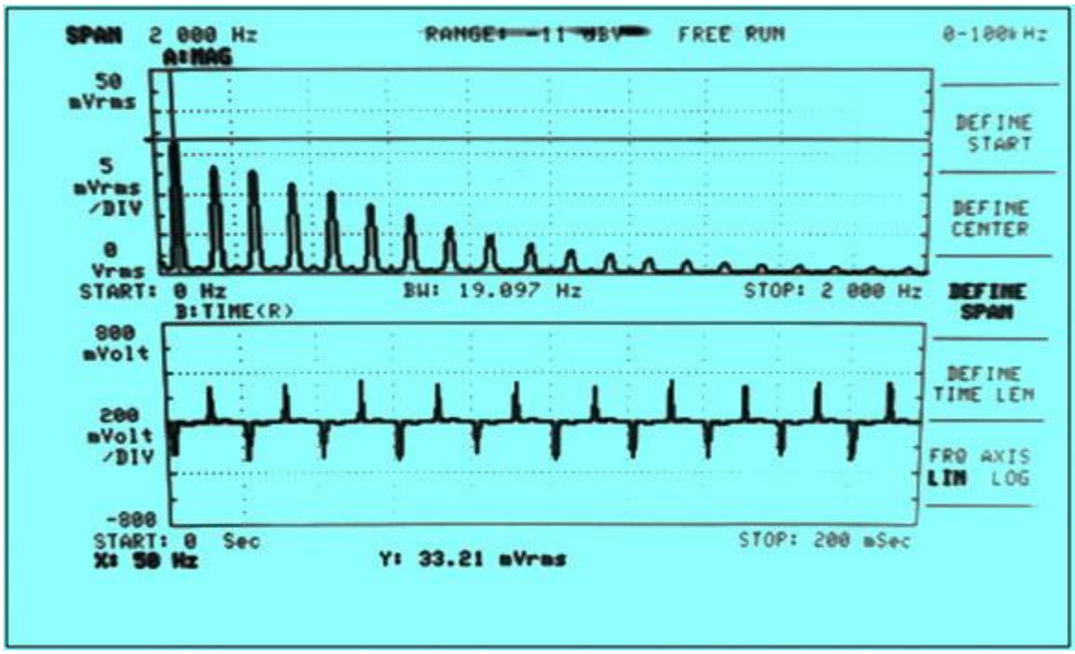

Figure (7/E) Time and frequency analysis of supply current at no-load

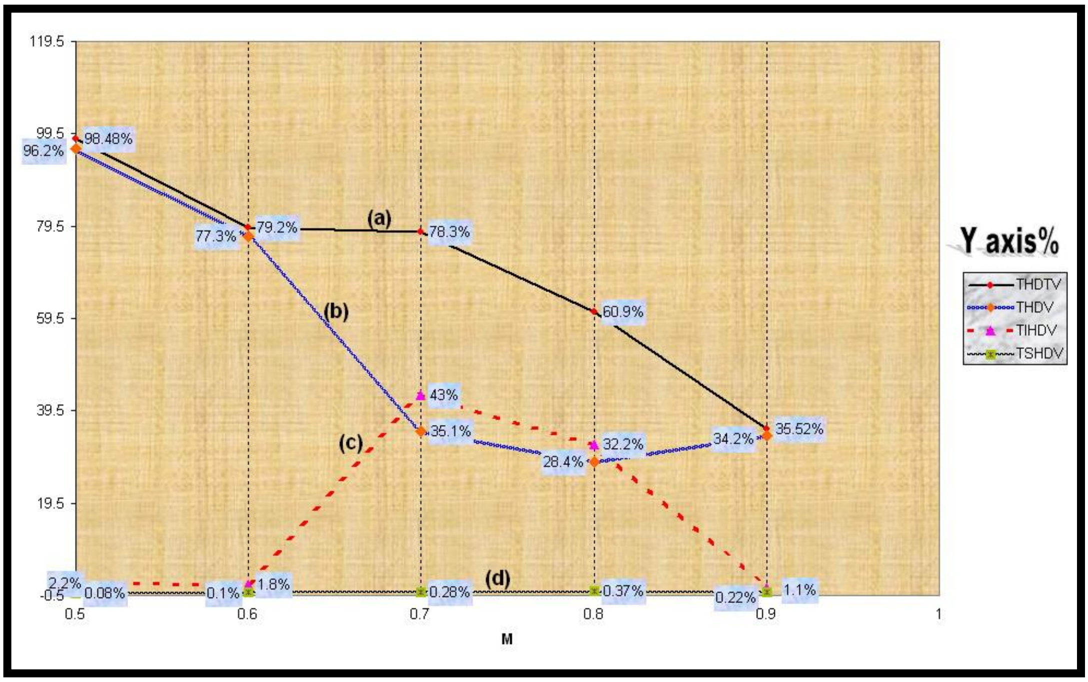

Figure (8) Harmonics analysis of Voltage at no-load{ (a) $THDT_V$ (b) THD_V (c) $TIHD_V$ (d) $TSHD_V$ }

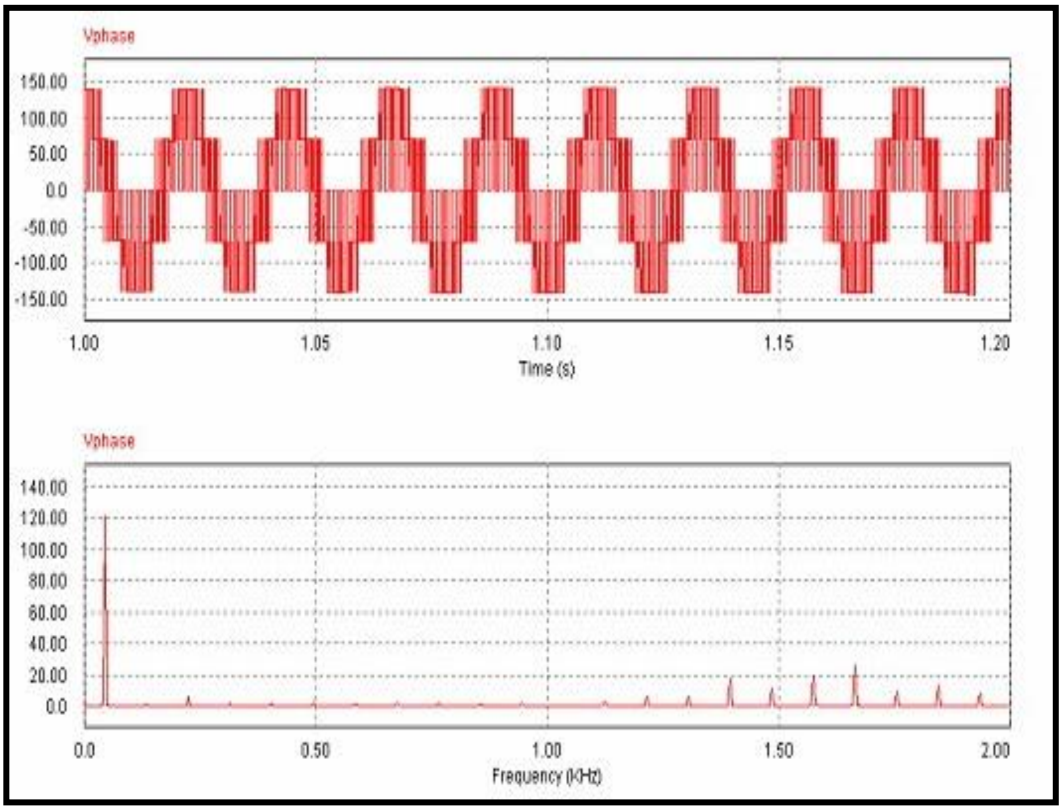

Figure (9) Time and frequenter analysis of Voltage at no-load at M=0.9 (Simulation state)

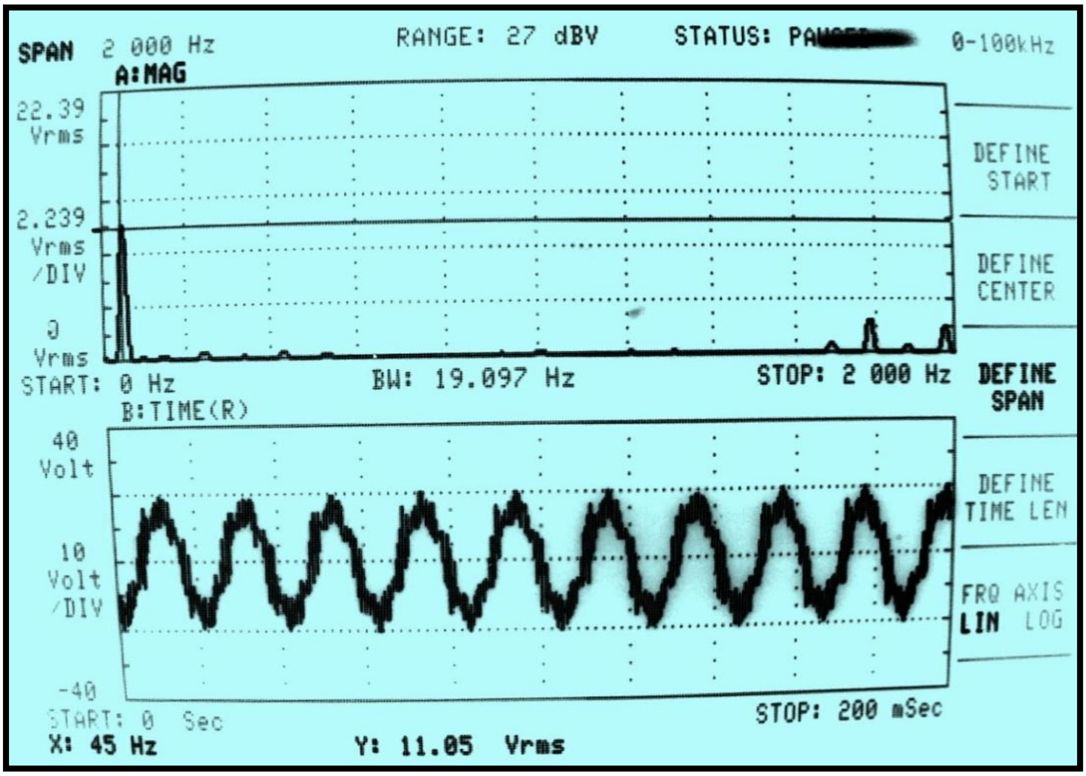

Figure (10) Time and frequenter analysis of Voltage at no-load at M=0.9 (Simulation state)