" THE HARMONIC CURRENTS GENERATED BY 6-PULSE , AC|DC CONVERTER WITH THE USE OF AC VOLTAGE REGULATOR "

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ABSTRACT

In this paper , a theoretical and experimental analysis of harmonic currents generated by 6-pulse , ac|dc converter with the use of ac voltage regulator is presented. The theoretical analysis is simulated using Fourier series analysis and Fast Fourier Transform (FFT) algorithm . The simulated analysis is validated with experimental results from 3-phase , 6-pulse , bridge converter rated at 4.2 Kw and connected to the 400 V , 50 Hz , ac power supply through a 3-phase , ac voltage regulator . The influence of dc load inductance on the ac harmonic current amplitudes is also evaluated.

الخلاصة

في هذا البحث ، تم القيام بالتحليل النظري و العملي للتيارات التوافقية الناتجة من اشتغال مجهز قدرة مستمر ، ثلاثي الطور ، ذو ست نبضات و باستعمال منظم فولتية في الطرف المتناوب .

استخدمت طريقتان للتحليل النظري و هما : تحليل سلسلة فورير (Fourier series analysis) و تحويل فورير السريع (Fast Fourier Transform) . تم إثبات النتائج النظرية عن طريق ربط مجهز قدرة مستمر ذو قدرة 4.2 كيلو واط و تمت مقارنة النتائج النظرية مع النتائج العملية . و أخيرا ،تم أيضا دراسة و قياس تأثير الخامد الحثي في الطرف المستمر على قيم التيارات التوافقية الناتجة في الطرف المتناوب.

KEYWORDS
Ac voltage regulator, ac\dc converter, harmonic currents, Fourier series , Fast Fourier Transform , experimental results.

INTRODUCTION

In the last 20 years, the static power converters are widely used in the industry for a variety of purposes such as, dc power supplies, adjustable speed drivers, uninterruptible power supplies, and high power induction heating equipment [J. Arrillaga et al,1997]. These converters draw nonsinusoidal (distorted) current from the main supply and act as a source of harmonics. Harmonics can be defined as " a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency"[IEEE standard 519 , 1993] .The harmonics for a 6-pulse converter, 50 Hz fundamental frequency are the fifth (250 Hz), the seventh (350 Hz), the eleventh (550 Hz)…etc.
The main sources of harmonics are rectifiers and arc furnaces. The power system problems, such as excessive losses and heating in motors and transformers, resonance, solid-state device malfunctions, metering and instruments error, and communication interference can be the direct result of the harmonics [J. S. Subjak et al ,1990 ; R. D. Henderson et al , 1994].Designers of industrial electrical plants are often requested to face the problem of elimination of harmonic currents injected by AC/DC converters. AC filters are a common solution for reduction of harmonic currents, but their design requires estimated of the harmonic currents injected in the ac supply system by converters. Estimation of harmonic currents are used to quantify the distortion in voltage and current waveforms and to determine whether resonant condition exist and how they might be reduced [Task Force , 1996].

This paper deals with the study of 3-phase , 6-pulse , AC\DC converter with the use of ac voltage regulator as a source of harmonics currents . The harmonic currents are analyzed theoretically and experimentally, and the effect of dc load inductance on their amplitudes is also evaluated.

HARMONICS PRODUCED BY AC\DC CONVERTERS

The supply line current drawn by a 6-pulse , AC\DC converter , (assuming resistive load and delta\star transformer), is shown in **Fig.1**. The Fourier series analysis of such waveform can shown to be :

$$I_A(wt) = \frac{5.739 \cdot I_{dm}}{p.T}\left[\sin(wt) + 0.2263\sin(5wt) - 0.1131\sin(7wt) + 0.0909\sin(11wt)\right. \qquad (1)$$

$$\left. - 0.065\sin(13wt) + 0.0567\sin(17wt) - 0.0454\sin(19wt) - ......\right]$$

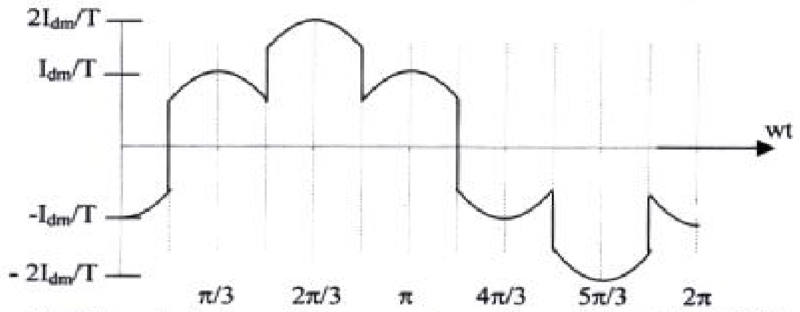

Fig.1 Supply line current waveform of 6-pulse ac\dc converter.

Therefore, the supply line current doesn't contain the even and triple harmonics and only contains a harmonic of order:

$$h = 6k \mp 1 \qquad (2)$$

In general, a converter of pulse number (q) generates ac current harmonics of order:

$$h = qk \mp 1 \qquad (3)$$

The harmonics produced by a 6-pulse , AC\DC converter will be the 5'th , 7'th , 11'th , 13'th , 17'th , 19'th ,… etc . For a 12-pulse converter the harmonics will be of order 11'th , 13'th , 23'th , 25'th , …etc. In practice , due to unbalance in the 3-phase supply voltages and firing circuits, some of small triple uncharacteristic harmonics of order (h=q.k-3) are appears in the system .

MODELING AND ANALYSIS OF AC\DC CONVERTER

3-phase , 6-pulse , AC\DC converters are considered the most important and practical in power electronics universe. Connecting a diode rectifier to an ac voltage regulator , through a transformer to a low voltage network (i.e. 0.4 Kv) as shown in **Fig.2** , is recommended to supply high dc current , low dc voltage (with dc power up to 150 Kw) [Mohammed A. Abdulsada , 1999 ; V. Subrahmanyam , 1997]. This allow the thyristors to control the lower primary current , which results in simpler more economical power circuit.

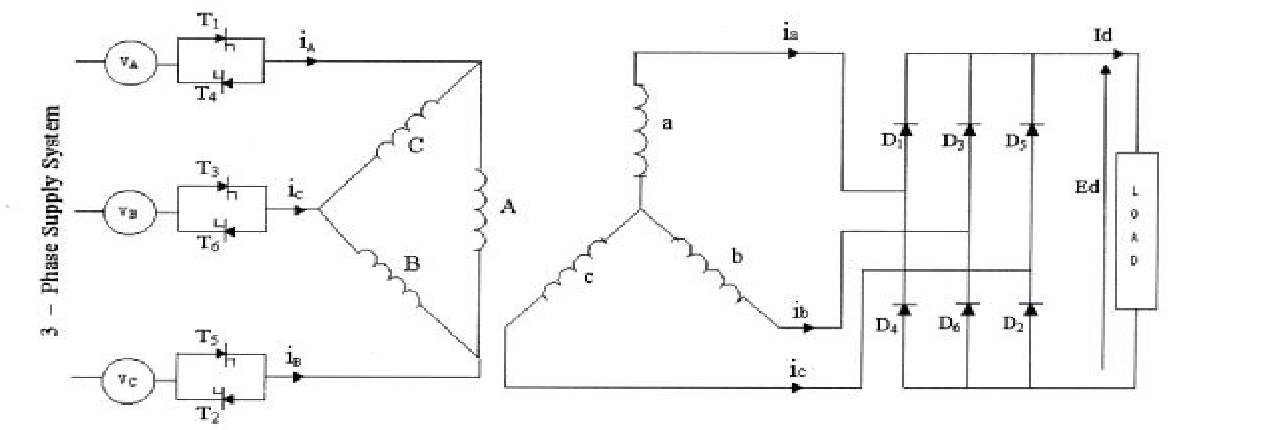

Fig.2 Circuit configuration of ac voltage regulator with 3-phase bridge rectifier.

To facilitate the analysis and operation of AC\DC converter model , the following assumptions can be made [J. Arrillaga , et al , 1997]:

i. The three-phase supply voltage are balanced and of sinusoidal waveforms.
ii. The thyristors are fired at equal time intervals, that is, at a constant delay angle.
iii. The supply leakage inductance is neglected.
iv. The load is assumed to be pure resistive and the effect of inductive load is considered in section (VI).

The operation of this model of AC\DC converter is depends on the firing angle values[G. K. Dubey, 1996]. On varying the firing angle α from 0^o to 30^o as measured from zero transit of the phase voltage , there is no control on the thyristors conduction . The thyristors start to be controlled fully after $wt=\frac{p}{6}$ of the transit of the phase voltage. During this period , the transformer is subjected to balance 3-phase supply voltages. At any instance of time, two diodes conduct one in the positive half and the other in the negative one. **Fig.3** shows the waveforms of dc output voltage and supply (primary) line current $i_A(wt)$ for this range of firing angle .

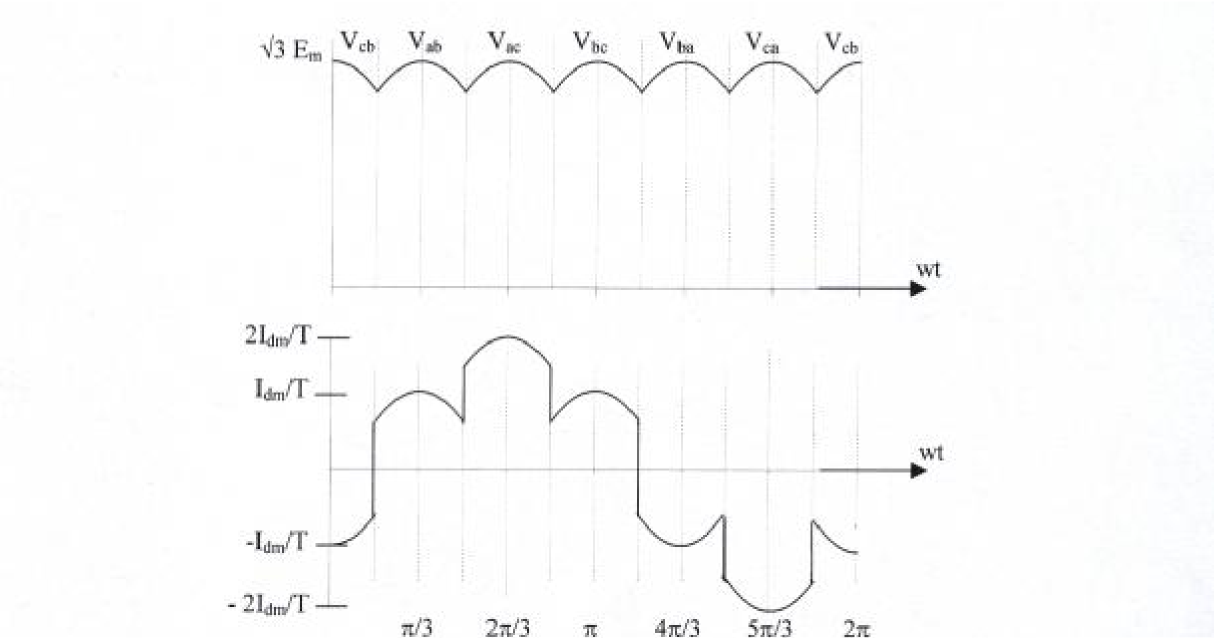

Fig.3 Output dc voltage and supply line current for uncontrolled region ,

$a \le 30^{\circ\circ}$

For the range of α , $30^{o^{\circ}} \le a \le 60^{\circ o}$, there are certain periods when three thyristors conduct and another when two thyristors conduct simultaneously. The relative duration of these periods depend on the value of α . When T_1 fired at α , T_5 & T_6 conduct along with it and the transformer is subjected to balance 3-phase supply voltages. At $w t = \frac{p}{3}$, T_5 is switched off as its phase voltage (V_c) or current reaches zero, but T_1 and T_6 continue to conduct , the transformer operates on single phase supply and this occurs in the range $\frac{p}{3} \le w t \le a + \frac{p}{3}$. During this period the voltage across phase C of delta connecting winding is equal to the line voltage V_{AC} whilst that across each of two other phases is equal to (1\2) V_{AC} . At $w t = a + \frac{p}{3}$, T_2 is fired and the transformer reverts to 3-phase operation with T_1 , T_6 & T_2 conducting till $w t = 2\frac{p}{3}$ when T_6 stops conduction as its current becomes zero. In the range $\frac{2p}{3} \le w t \le a + \frac{2p}{3}$ T_1 and T_2 conduct making the transformer operates on single phase supply again . At $w t = a + \frac{2p}{3}$, T_3 gets positive voltage and start conduction with a firing pulse and the transformer reverts to 3-phase operation with T_1 , T_2 and T_3 this continues till $w t = p$ where T_1 stops conduction. The next negative half cycle begins from $w t = a + p$ and the sequence of alternative two-thyristors and three-thyristors conduction is repeated for the rest of the cycle, for example; T_2 , T_3 and T_4 conducting for the range

$a + p \le w t \le \frac{4p}{3}$, T_3 and T_4 conducting the range $\frac{4p}{3} \le w t \le a + \frac{4p}{3}$, and so on. **Fig.4.a** illustrates the waveforms of the line-to-line voltages (heavy line) supplied to the transformer for firing angle 45^o .
It may be noted that the period during which three-thyristors conduct simultaneously decrease as the firing angle is retarded and when the firing angle is 60^o or more three-thyristors simultaneous conduction ceases.

Fig.4.b and Fig.4.c show the waveforms for firing angles of 60^o and 90^o. In this case, when T_1 is fired at α , T_5 is turned off simultaneously and T_1 and T_6 start conducting. When T_2 is fired at $\frac{p}{3}$ later , T_6 is turn off and the current flow through T_1 and T_2 . At $w t = a + \frac{2p}{3}$, T_3 is fired but T_1 stops conduction, therefore T_2 and T_3 conduct . The sequence of alternate two-thyristors conduction is repeated during each $\frac{p}{3}$ period. This operation of the circuit extends over the firing angle range from 60^o to 90^o .
For the range of firing angle greater than 90^o , discontinuous conduction occurs. **Fig.4.d** shows the waveforms corresponding to a firing angle 120^o .At instant of α , firing pulses are applied to T_1 and T_6 , thereby initiating a flow of current through the supply lines A and C . At $w t = a + \frac{p}{3}$, T_1 is fired once again with T_2. Similar operation is repeated in the other two phases during the rest of the cycle. This mode of operation describes the operation of firing angles from 90^o to 150^o or more , no current will be delivered to the transformer because each time two thyristors are firing and they block the reverse voltages. Thus, complete control of voltage is obtained within a firing angle range 0^o to 150^o .
If the transformer has a T turns ratio , then the voltage waveforms shown in **Fig.4** will be transformed to the secondary side divided by T , it may be noted that the dc output voltage is not affected by varying the control angle from zero to 30^o ; it changes at firing angle greater than 30^o . **Fig.5** shows the waveforms dc output voltage for different firing angles.

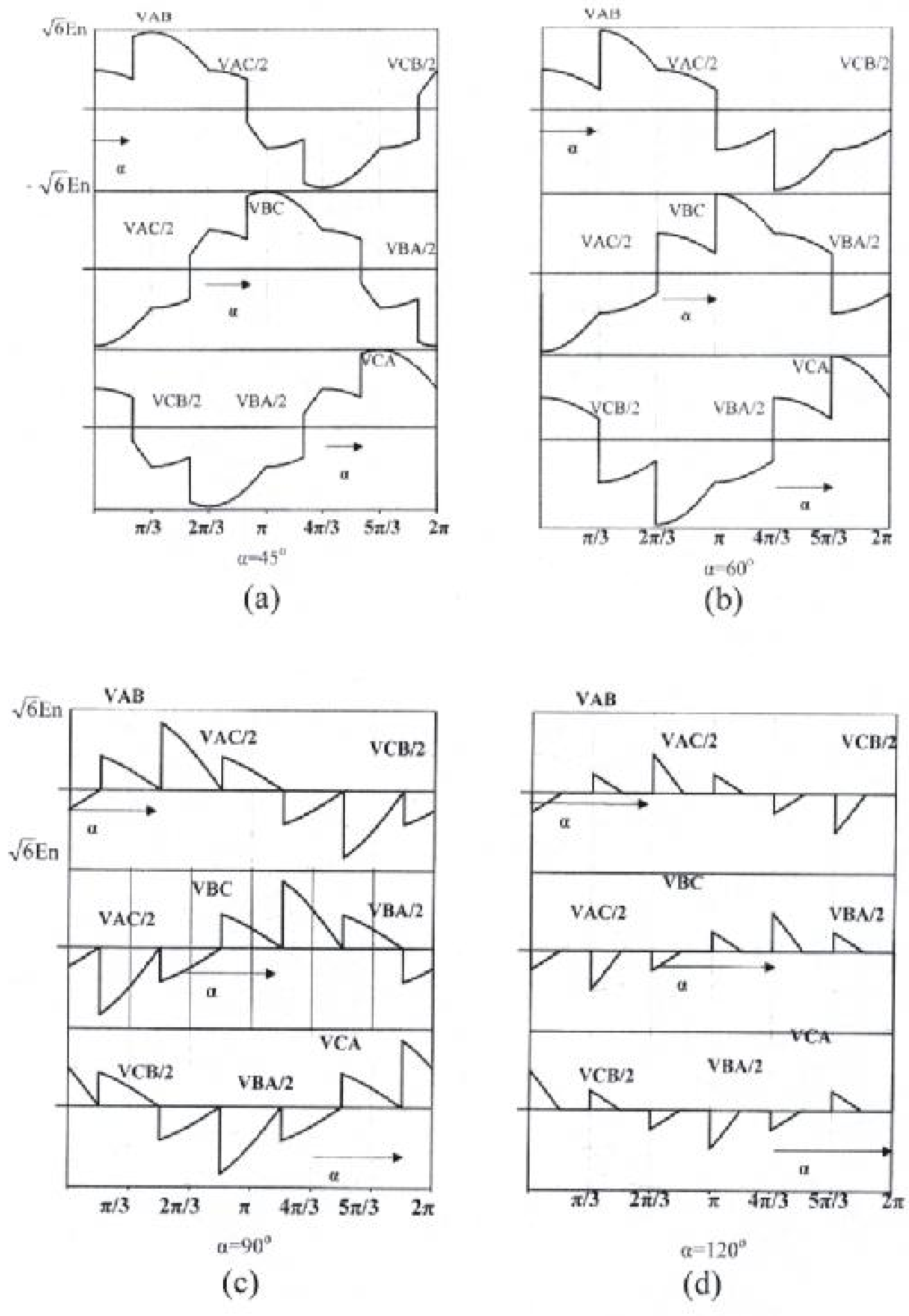

Fig.4 Primary line voltage for different firing angles.

Both the load current and the secondary line current are made up of parts of sinusoids. The supply line current (I_A) , Which equal to the difference of appropriate of two delta currents , and the secondary line currents waveforms are shown in **Fig.6** for different firing angles.

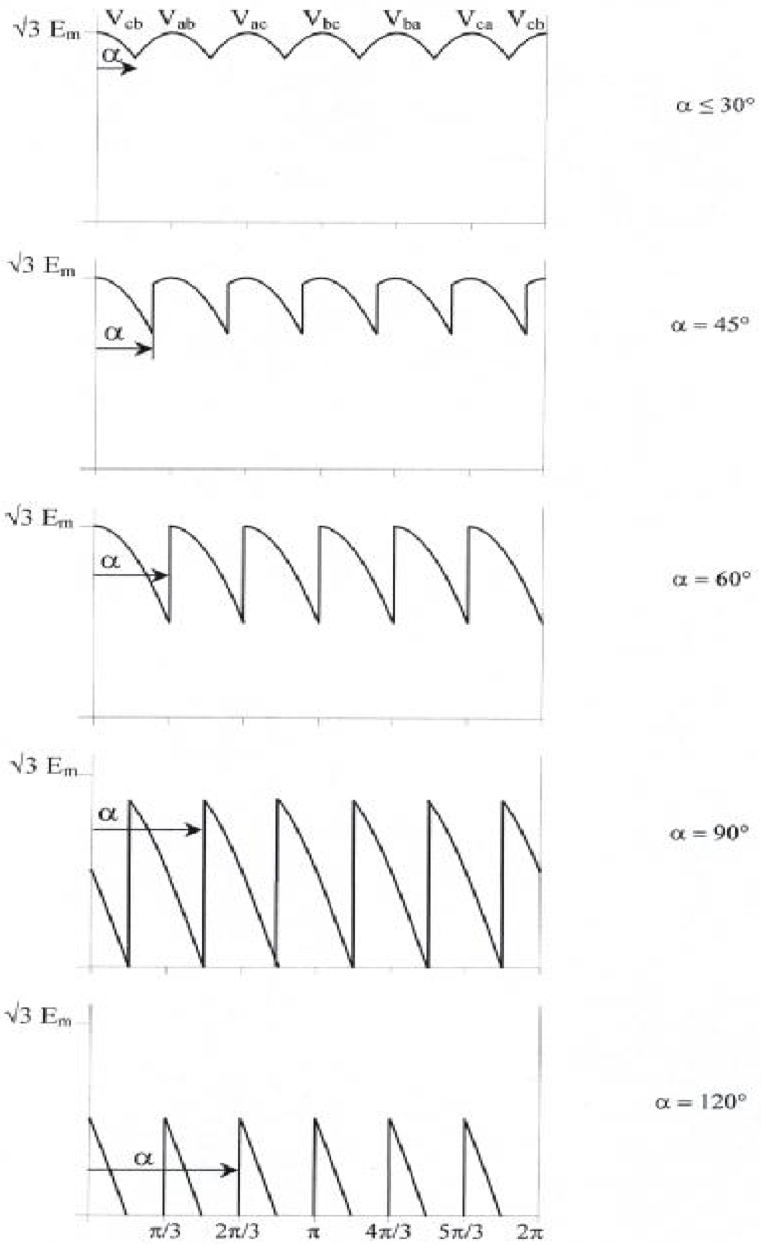

Fig.5 Instantaneous output dc voltage for different firing angles.

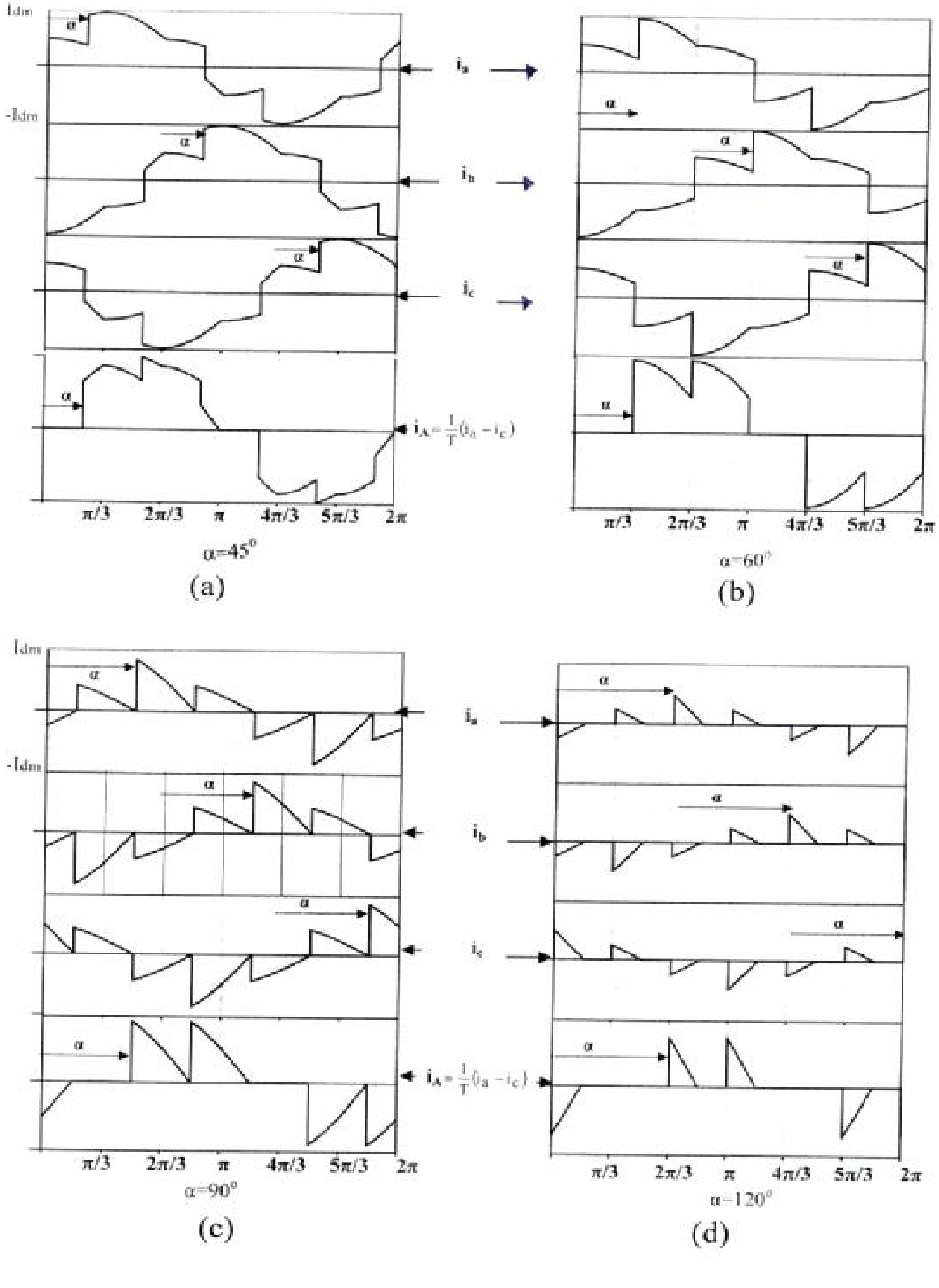

Fig.6 Secondary and supply line currents for different firing angles.

SIMULATION AND EXPERIMENTAL RESULTS

The harmonic current magnitudes are evaluated using two methods; Fourier series (FS) decomposition and Fast Fourier Transform (FFT).The FFT method described the current waveform in the time domain and can easily be performed via computer software to arrive at the constituent harmonics. The MatLap software is used to compute the FFT of the supply line current and the complete data vector input takes exactly one period to sample. The sampling rate is taken to be 180 sample per complete period (i. e. 180 sample\ 20 msec.)[Mohammed A. Abdulsada , 1999].
A 3-phase , 6-pulse , 4.2 Kw is assembled and connected to 0.4 Kv power supply through a 3-phase , ac voltage regulator. A 5 KVA , delta\star transformer of 19 turns ratio (step down) is used and the load is a pure resistive of 0.15 Ω . **Fig.7** shows the experimental waveform of the dc output voltage for different firing angle

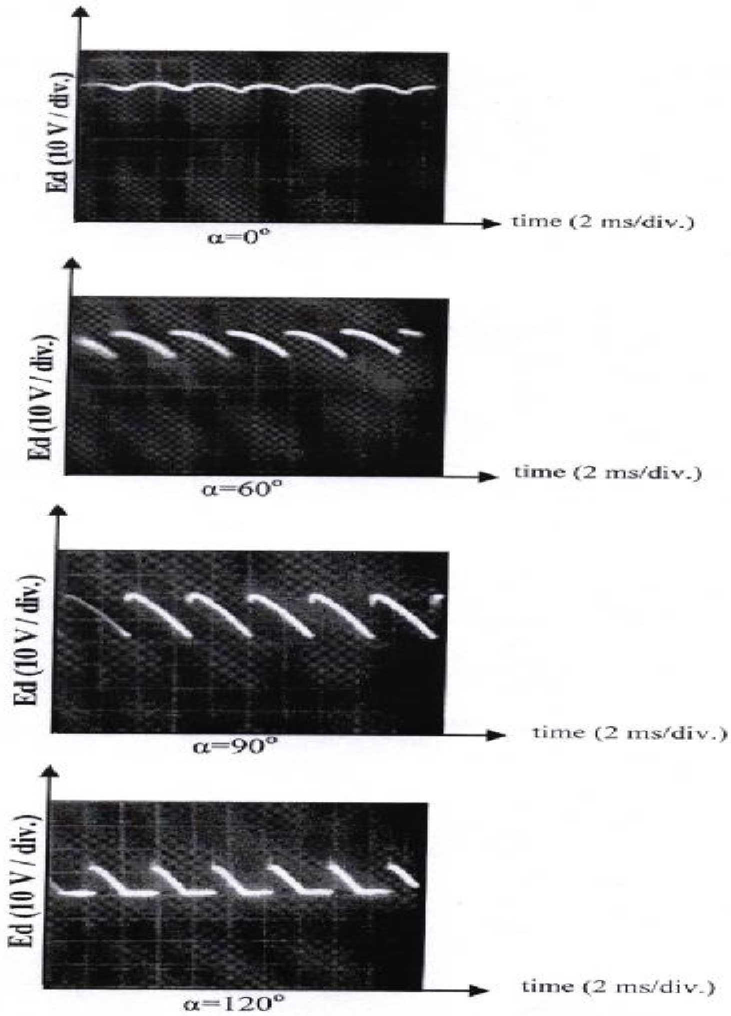

Fig.7 Experimental waveforms of output dc voltages.

Fig.8 shows the experimental waveform of the supply line current and the corresponding frequency spectrum .A comparison of the supply line current harmonics computed by the two simulation methods (FS and FFT) and the experimental results is shown in **Fig.9** . The harmonics computed theoretically by the two methods are seen to be very close to each other (approximately equal). There is of slight difference between the theoretical and experimental results of the supply line current harmonics because the theoretical results of the AC\DC converter are never fulfilled exactly in the practice.

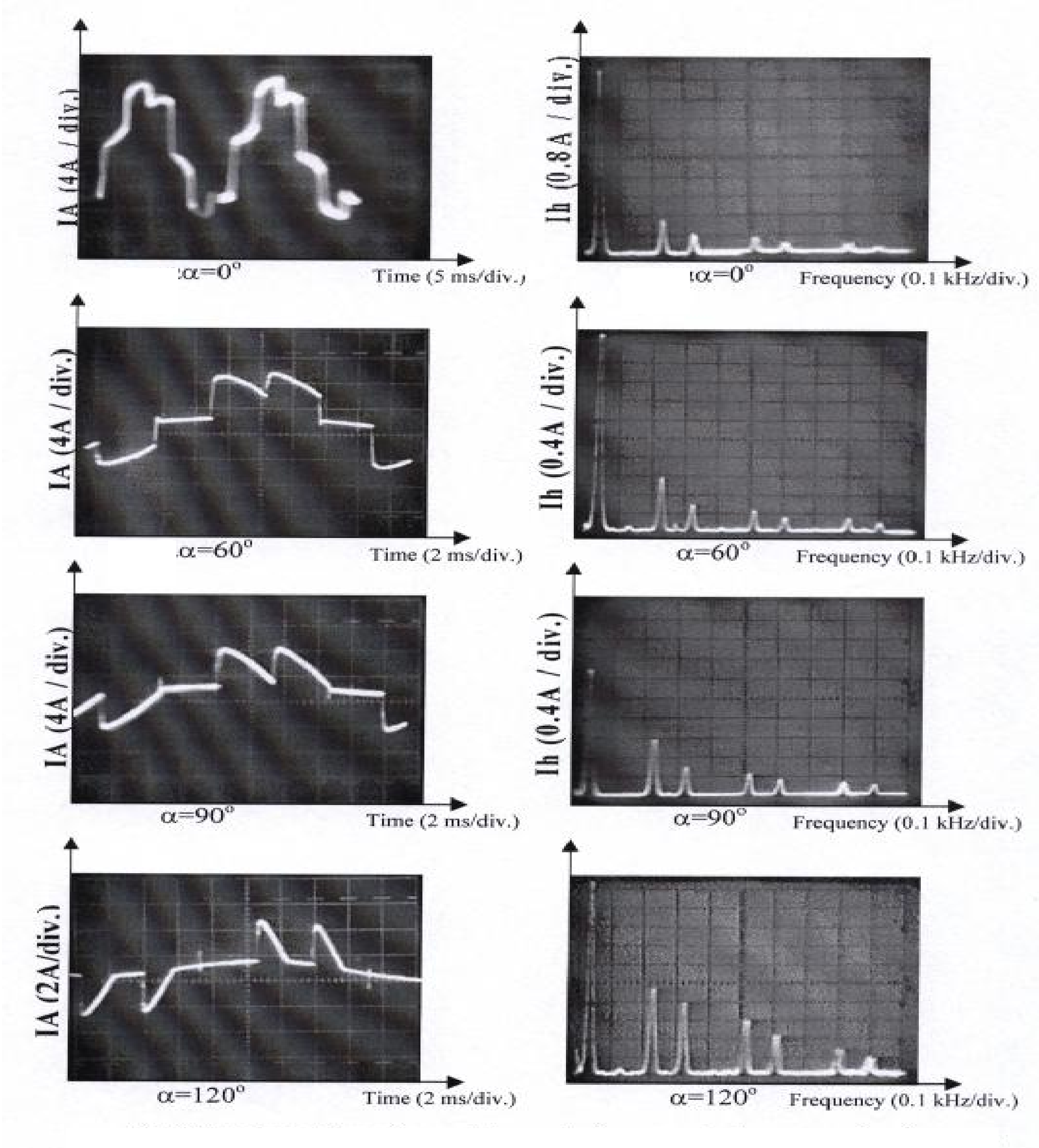

Fig.8 Experimental waveforms of the supply line current and corresponding frequency spectrum.

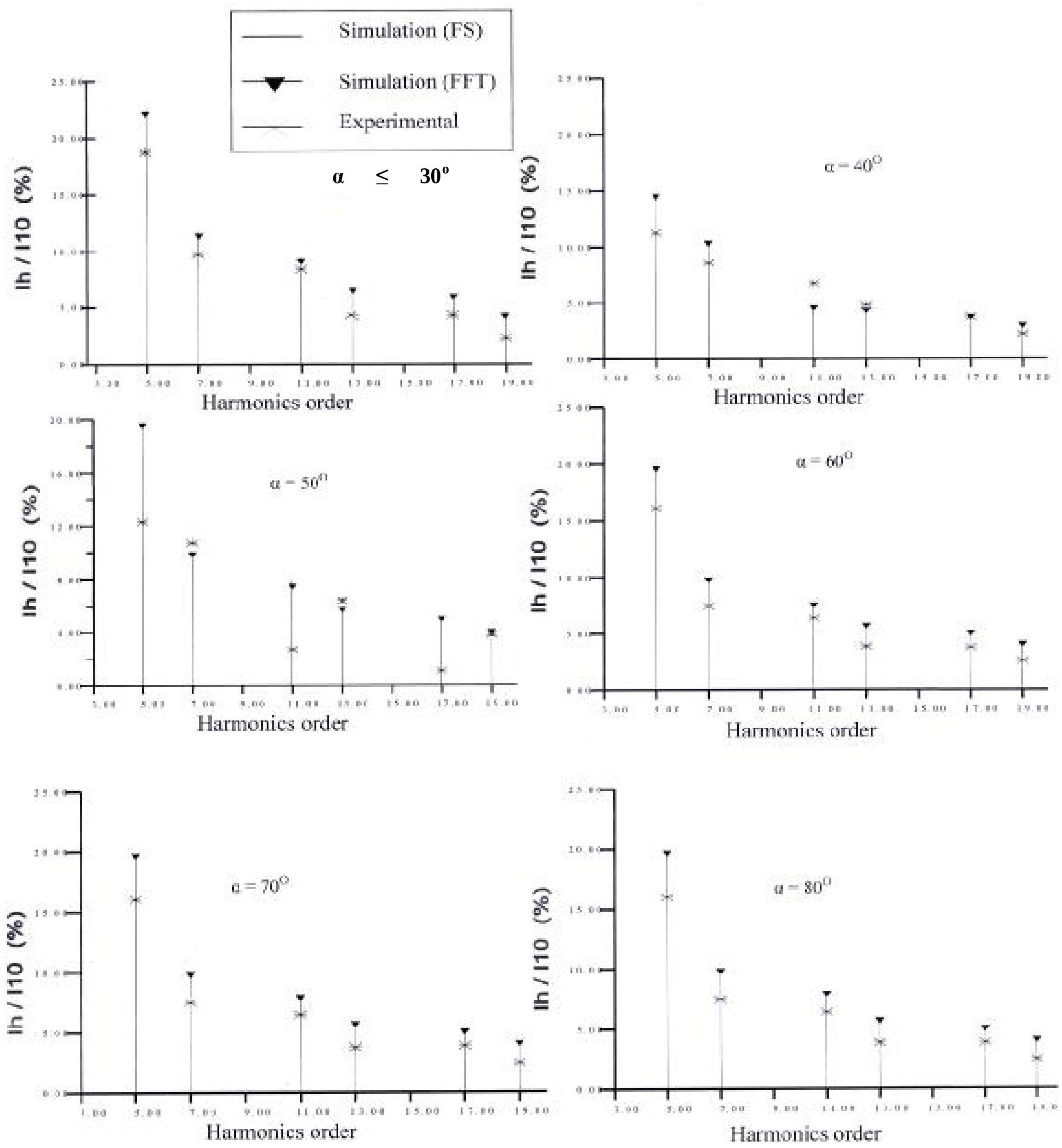

Fig. 9 Simulation and experimental results of supply line current harmonics amplitude as a percentage of fundamental ($I_h \backslash I_{1o}$).

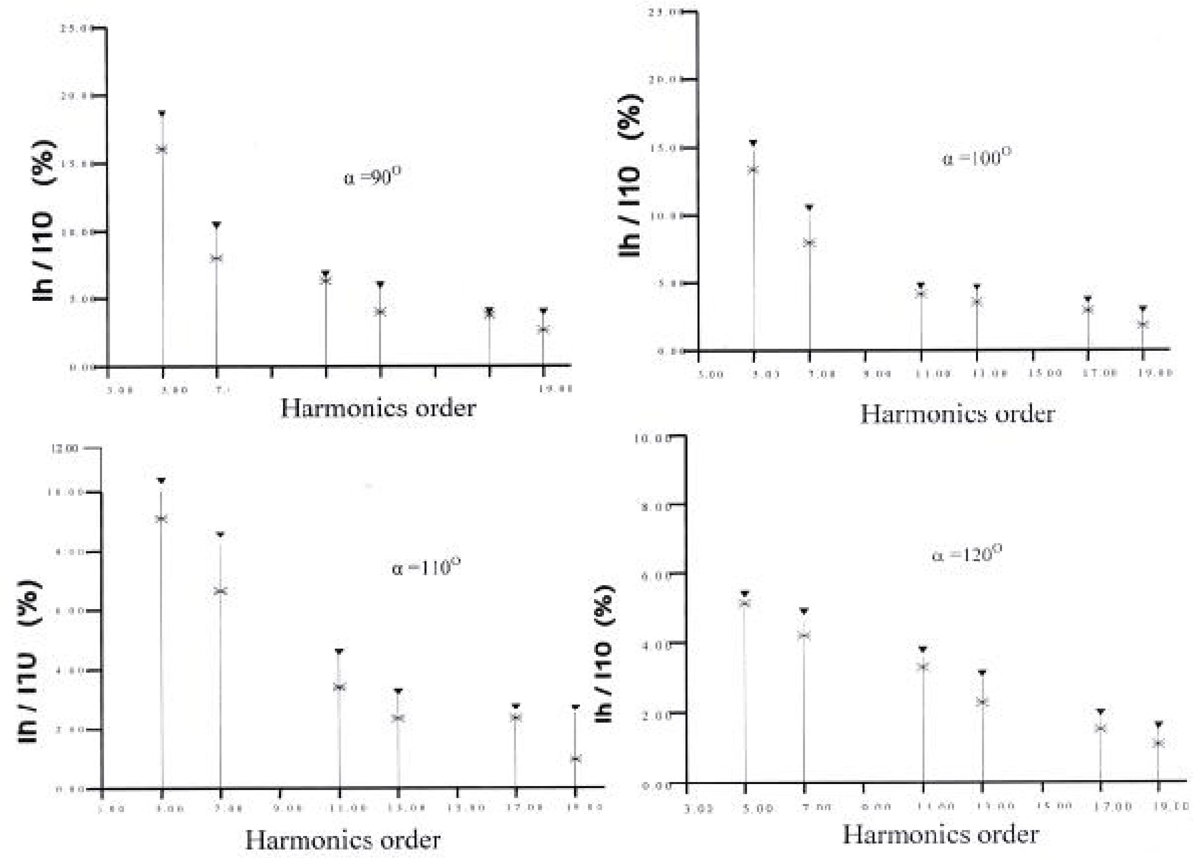

Fig. 9 Continued

EFFECT OF DC INDUCTIVE LOAD

If the load on the dc side includes a large series inductance (infinite inductance) then the load current approaches the waveform of pure dc level [V. Subrahmanyam ,1997]. If the supply leakage inductance remains negligible, the supply line current is free from ripple and the waveform with uncontrolled region (i.e. $a \le 30^{\circ\circ}$) will be as shown in **Fig.10**. The Fourier series of such waveform can be shown to be:

$$i(wt) = \frac{6I_d}{p\,.T}\left[\sin\,(w\,t) + \frac{1}{5}\sin\,(5\,w\,t) - \frac{1}{7}\sin\,(7\,w\,t) - \frac{1}{11}\sin\,(11\,w\,t) + \frac{1}{13}\sin\,(13\,w\,t) + \frac{1}{17}\sin\,(17\,w\,t) - \frac{1}{19}\sin\,(\sin 19\,w\,t) - ....\ ......\right] \quad (4)$$

The harmonic current magnitudes relative to the uncontrolled fundamental component with zero and infinite dc inductance are given in **Table .1**.

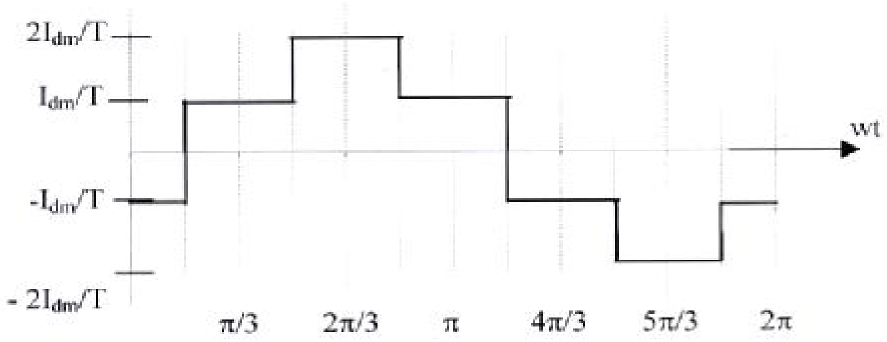

Fig. 10 supply line current with infinite dc inductance.

Table 1 Ac harmonics currents with zero and infinite dc inductance conditions.

Order of Harmonics	*Magnitude of harmonic current*		*Difference (%)*
	$L_{d=0}$	$L_{d=\infty}$	
1	1	1	0
5	0.226	0.200	13
7	0.113	0.143	21
11	0.091	0.091	0
13	0.065	0.077	16
17	0.0567	0.0588	4
19	0.0454	0.0526	14

From **Table.1** , it may be seen that the fundamental component (I_{1o}) is the same , the ($I_5 \backslash I_{1o}$) is decreased from 0.226 to 0.2 , ($I_{11} \backslash I_{1o}$) is approximately the same , this due to the fact that the 11'th harmonic current amplitude is scarily relative to ripple , whilst all other harmonics are increased to some extent .**Table.2** gives the experimental values of harmonic currents as a percentage of fundamental (i.e. ($I_h \backslash I_{1o}$).**Fig.11** shows the experimental waveforms of the supply line current and corresponding frequency spectrum for different firing angles when a (0.1) mH inductive chock is connected in series with the resistive load.

Table 2 Experimental values of harmonic currents as a percentage of fundamental ($I_h \backslash I_{1o}$ %)

	harmonic currents as a percentage of I_{1o} (%)											
Order \ α	≤ 30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	150°
5	16.84	9.447	11.57	15.26	14.73	13.68	11.57	10.0	7.26	3.68	1.57	0
7	10.52	8.94	7.89	4.73	2.94	2.89	3.89	4.73	4.73	2.89	1.47	0
11	8.42	6.31	3.05	5.26	4.52	4.00	3.36	1.68	1.36	1.894	1.36	0
13	4.82	4.21	4.21	2.63	1.26	0.842	1.57	1.89	0.526	1.05	1.00	0
17	4.5	3.15	1.57	8	2.63	2.1	1.73	0.631	1.315	0.26	1.00	0
19	2.36	1.84	2.36	1.89	1.00	0.52	0.84	0.578	0.789	0.26	0.789	0

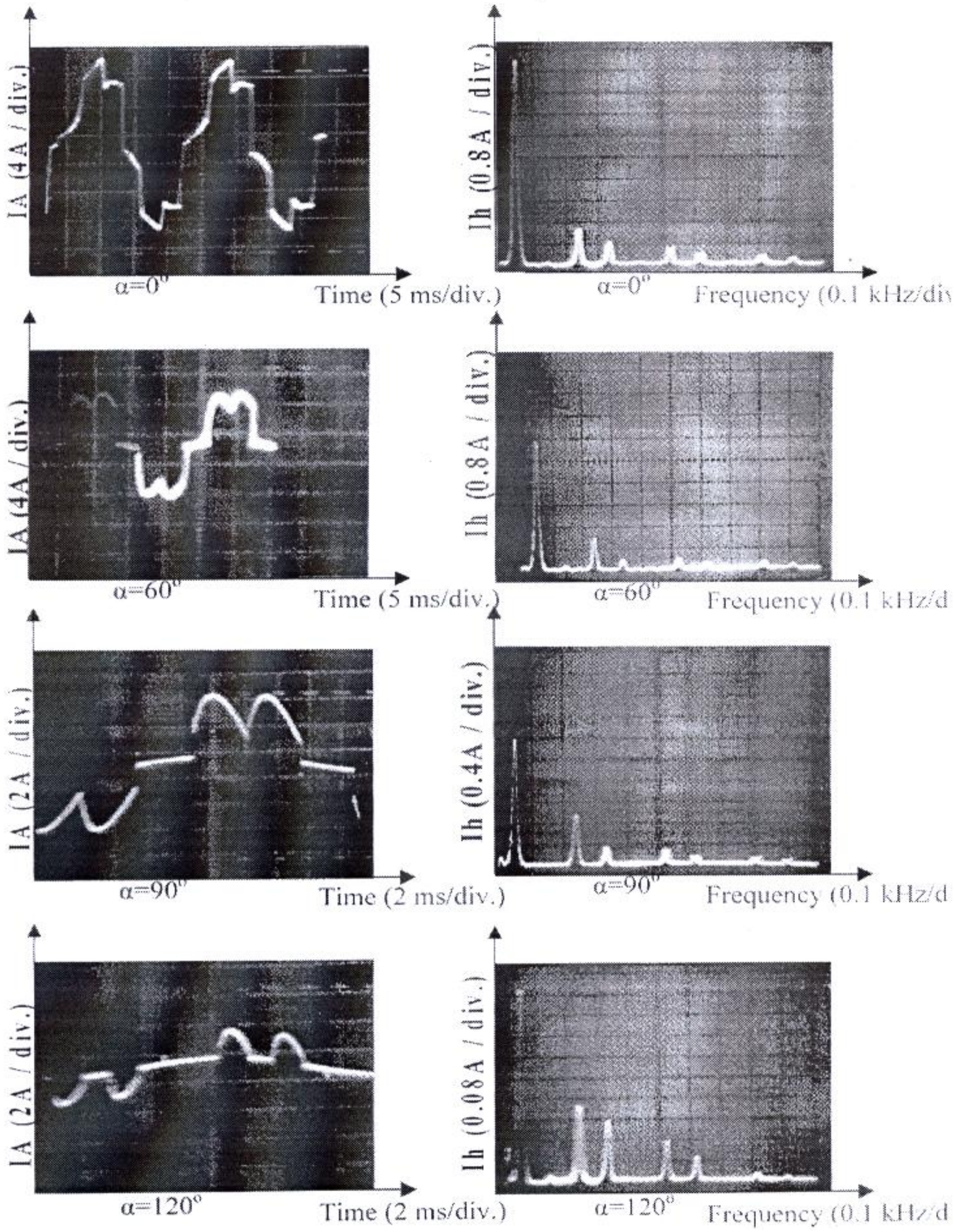

Fig. 11 Experimental waveforms of the supply line current and corresponding frequency spectrum for an inductance in series with resistive load.

CONCLUSION

In this paper , the harmonic currents produced by 3-phase , 6-pulse , AC|DC converter with the use of ac voltage regulator at the supply side are analyzed theoretically and experimentally. The theoretical analysis is simulated using Fourier series analysis and Fast Fourier Transform (FFT) algorithm . A 4.2 Kw , (26 v \ 162 A) 3-phase, AC|DC converter is assembled and the experimental measurements of harmonic currents were carried out . The dominant harmonics in the supply line current are found to be the first two odd harmonics (5\th and 7'th) and the harmonics components in practice are some how less than the theoretical because of commutation effect . The effect of inserting a 0.1 mH inductive chock in series with the resistive load is evaluated . The maximum reduction in the harmonic currents is achieved at $a \leq 90^{o}$. The model of AC|DC converter ,which considered in this paper , is preferable to be used at low voltage level network to produce low dc voltage , high dc current . This allow the thyristors to control the lower primary current , which results in simpler more economical power circuit.

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LIST OF SYMBOLS

a = Firing angle.

E_n = ac supply line-to-neutral voltage (rms).

E_m = secondary line-to-neutral voltage (maximum).

h = order of harmonic.

i (w t) = Instantaneous supply current.

I_d = Average value of dc load current.

I_{dm} = crest value of dc load current.

I_{lo} = fundamental component of I_L , assuming zero phase control.

K = Integer no. , 1,2 ,3 , …

L_d = Inductance of the dc reactor.

q = converter pulse number.

T = Transformer turns ratio.

V_A, V_B, V_C = Instantaneous line-to-neutral 3-phase supply voltages.

V_{AB}, V_{BC}, V_{AC} = Instantaneous line-to-line 3-phase supply voltages.