"THE EFFECT OF VARIATION OF NONLINEAR LOAD ON POWER FACTOR OF THE AC SUPPLY NETWORK "

By

Mr. Mohammed Abdulla Abdulsada ,
Electrical Engineering Dept.
Faculty of Engineering \ Tobruk
Omar Al-Mukhtar University

Praf. Dr. Ali A. Al-killidar & Dr. Ziad Al-Azawi
Electrical Engineering Dept.
College of Engineering
University of Baghdad

ABSTRACT

The aim of this paper is to evaluate the effect of the converter system on the power factor of the supply network .Therefore a 3-phase, 6-pulse , bridge converter is assembled and connected to a power supply through a 3-phase ac voltage regulator .The theoretical analysis is simulated using Fourier series analysis and Fast Fourier Transform (FFT) algorithm . The experimental measurements of distortion factor , displacement factor and total power factor are recorded . The experimental results are shown to be coincident with the theoretical results. The consideration of power factor improvement relative to distortion and displacement factors is discussed.

الخلاصة

إن الهدف من هذا البحث هو تأثير مغير القدرة على معامل القدرة (power factor) للشبكة المجهزة. لذلك تم تجميع و ربط مجهز قدرة مستمر ثلاثي الطور ذو ست نبظات 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 استنتاج النتائج العملية لمعامل الإزاحة (displacement factor) و معامل التشويه (distortion factor) و معامل القدرة و تم مقارنة النتائج النظرية مع النتائج العملية . تم مناقشة طرق تحسين معامل القدرة و ذلك عن طريق تحسين معامل الإزاحة و معامل التشويه .

KEYWORDS: power factor, displacement factor, distortion factor, harmonic currents, power factor correction, effect of dc inductance.

INTRODUCTION

Power factor has increasingly become a topic of discussion when specifying loads and ac\dc power sources. When large nonlinear loads are connected to utility systems, significant harmonic currents are produced. The converter harmonics cause increased heating of the utility and other customer equipment and can lead to system resonance. Therefore, the harmonics need to be taken into account in various system evaluations[L. Cividino , 1992].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 – 1992, 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 most noticeable problem associated with electrical rectification was the inherently poor power factor of the power system. The power factor of a circuit is universally defined as " the ratio of the active or average power, in watts, to the apparent power or product rms volt times rms ampers at the terminals". The above definition is based on the assumption that loads on the system have liner voltage-current characteristics and that harmonic distortion of the current and voltage is not significant. With these assumptions, the power factor is equal to the displacement factor. Harmonic distortion in the current and voltage caused by AC/DC converters in the system changes the way power factor must be defined[W. Shepherd and P. Zand , 1979].In this case, the total power factor is defined as "the ratio of the total power input, in watt, to the total volt-amperes in the circuit" , the total power factor made up of two components; displacement and distortion factors. The displacement factor is "the ratio of the active power of the fundamental wave, in watt, to the apparent power , in volt-amperes"[P. Filipski S.,1991].This is the power factor that is measured by metering. The distortion factor is that part associated with the presence of harmonic current and voltage [IEEE standard 519 – 1992, 1993].

The association of total power with displacement and distortion factors is important because it highlights the factors which determine the overall power factor of a system. A poor power factor can be the result of either a significant phase difference between the voltage and current at the load terminals, or it can be due to a high harmonic content or distorted/discontinuous current waveform. Poor load current phase angle is generally the result of an inductive load such as an induction motor, power transformer, lighting ballasts, welder or induction furnace. A distorted current waveform can be the result of a rectifier, variable speed drive, switched mode power supply, discharge lighting or other electronic load.

The power factor correction (PFC) can be made if the distortion factor and displacement factor are improved. The distortion factor is increased by reducing the harmonic currents from entering the main system by providing a shunt filter of low impedance to the harmonic frequencies. These shunt filters also supplies all or part of the reactive power consumed by the converter, the remainder being supplied by shunt capacitor banks Which used to improve the displacement factor. A large number of topologies and control strategies are implemented to achieve rectification in 3-phase supply with high power factor[H. Mao , etal , 1997 ; Y. Jang and M. Jovanovic , 1998].

The objective of this paper is to analyze the supply total power factor of the 3-phase, 6-pulse , ac\dc bridge converter with the use of 3-phase ac voltage regulator theoretically and experimentally.

* DISPLACEMENT FACTOR, DISTORTION FACTOR AND TOTAL POWER FACTOR

The angle between the fundamental supply voltage and the fundamental component of the supply line current is known as displacement angle (ϕ 1). The cosine of the input displacement angle is the displacement factor (cos ϕ 1). The displacement factor can be also defined as the ratio of the active power to the fundamental apparent power.

The distortion factor is defined as the ratio of the rms amplitude of the fundamental component of the input supply line current, to it is total rms amplitude, that is:

$$\cos\delta = \frac{I_1}{I_L} \qquad (1)$$

The total power factor is defined as the ratio of the total active power input, in watt, to the total apparent power in the circuit, that is:

$$\mathrm{PF} = \frac{Total\ active\ power\ input\ (W)}{Total\ apparent\ power\ input\ (VA)} \qquad (2)$$

* POWER FACTOR UNDER LINEAR AND NONLINEAR LOADS

The linear load is that load draw a sinusoidal current wave when supplied by a sinusoidal supply voltage. Only the fundamental component of the supply voltage and line current are exist. The active input power could be described as:

$$P = \frac{1}{2\pi}\int_0^{2\pi} e(\omega t).i(\omega t).d\omega t = \frac{1}{2\pi}\int_0^{2\pi} \sqrt{2}\, E_n \sin(\omega t)\ .\sqrt{2}\, I_1 \sin(\omega t + \varphi_1)\, d\omega t \qquad (3)$$

Which leads to:

$$P = En\ .\ I_1.\ \cos\varphi_1 \qquad (4)$$

The apparent power will be given by :

$$S = S1 = En \,.\, I_1 \tag{5}$$

By definition the total power factor is given by:

$$PF = \frac{P}{S} = \frac{P}{S_1} = \cos\phi_1 \tag{6}$$

It can be deduced that in the linear loads the total power factor is equal to the displacement factor.

In the case of nonlinear load the current drawn from the main supply voltage is non-sinusoidal (distorted) and can be represented by Fourier summation of the fundamental and harmonics components:

$$I(\omega t) = \sqrt{2}\, I_1 \sin(\omega t + \phi_1) + \sum_{h=2}^{\infty} \sqrt{2}\, I_h \sin(h\omega t + \phi_h) \tag{7}$$

The active power drawn from the supply system due to each harmonic component of current is given by:

$$P_h = \frac{1}{2\pi} \int_0^{2\pi} \sqrt{2}\, E_n \sin(\omega t) . \sqrt{2}\, I_h \sin(h\omega t + \phi_h)\, d\omega t = 0 \tag{8}$$

That means the active power transferred only by combination of voltage and current components of the same frequency

The total rms line current and total apparent power is given by:

$$I_L = \sqrt{I_1^2 + \sum_{h=2}^{\infty} I_h^2} = \sqrt{\sum_{h=1}^{\infty} I_h^2} \tag{9}$$

$$S = E_n . I_L = E_n . \sqrt{\sum_{h=1}^{\infty} I_h^2} \tag{10}$$

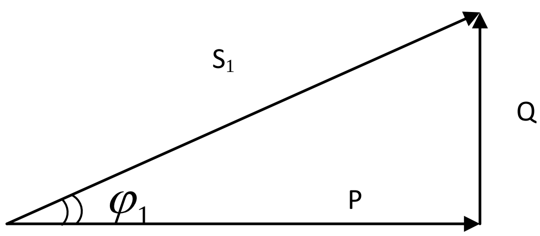
By the use of Eq. (1), the total power factor will be :

$$PF = \frac{I_1}{\sqrt{\sum_{h=1}^{\infty} I_h^2}} . \cos\phi_1 = \frac{I_1}{I_L} . \cos\phi_1 \tag{11}$$

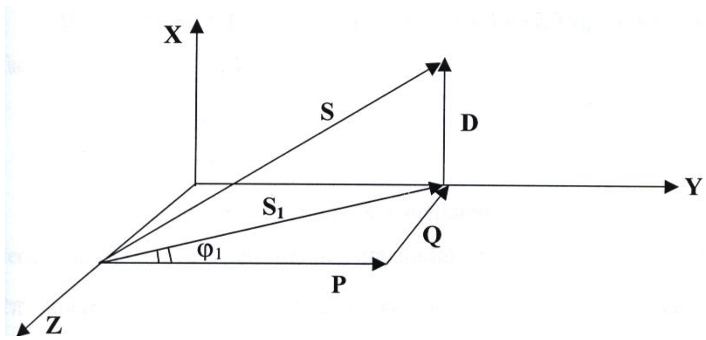
Thus, the power factor of nonlinear load is made up of product of two components: displacement Factor (cos φ_1) and the distortion factor ($I_1 \backslash I_L$) which associated with the harmonics present.

Since, by definition, I_L is greater than I_1 due to the presence of harmonics current component, the distortion factor is less than unity and hence the power factor is less than unity even in those cases where cos ϕ_1 has it is maximum value of unity.

The distortion power (D) is created by the combination of voltage and current components of harmonic current . Only fundamental frequency powers (P, Q and S_1) can be represented by a triangle phasors as shown in **Fig.1.a** .The total apparent power and distortion power are only numerical values. The distortion power is perpendicular to the plane P, Q and S1, so that the total apparent power (S) is conventional to represented geometrically by a three dimensional representation (space diagonal) as shown in **Fig.1.b[**Task Force , 1996].



a.



b.

Fig.1 Power phasor diagram (a) linear load (b) nonlinear load.

* POWER FACTOR IN TERMS OF FOURIER SERIES COEFFICIENTS

The total power factor can be calculated also by using the Fourier series analysis. For a periodic non-sinusoidal current I(ωt) of a periodicity 2π radians the Fourier coefficient a_1 and b_1 for the peak value of the fundamental line current are:

$$a_1 = \frac{1}{\pi}\int_0^{2\pi} i(\omega t).\cos \omega t \, d\omega t \quad (12)$$

$$b_1 = \frac{1}{\pi}\int_0^{2\pi} i(\omega t).\sin \omega t \, d\omega t \quad (13)$$

The rms value of fundamental line current (I_1) is given by:

$$I_1 = \sqrt{(a_1^2 + b_1^2)/2} \tag{14}$$

The displacement factor can be shown to be:

$$\cos\phi_1 = \cos\left[\tan^{-1}\frac{a_1}{b_1}\right] = \frac{b_1}{\sqrt{a_1^2 + b_1^2}} \tag{15}$$

The distortion factor is given by:

$$\cos\delta = \frac{\sqrt{a_1^2 + b_1^2}}{\sqrt{2}\, I_L} \tag{16}$$

The total power factor is found to be :

$$PF = \frac{b_1}{\sqrt{2}\, I_L} \tag{17}$$

*** MODELING AND ANALYSIS OF AC\DC CONVERTER**

At low ac level network (i.e. 0.4 Kv) , 3-phase , 6-pulse , AC\DC bridge converters are recommended when dealing with power up to 150 Kw. In case of high dc current , it is preferable to control the supply ac voltage by means of 3-phase ac voltage regulator as shown in **Fig.2**.This allow the thyristors to control the lower primary current , which results in simpler more economical power circuit.

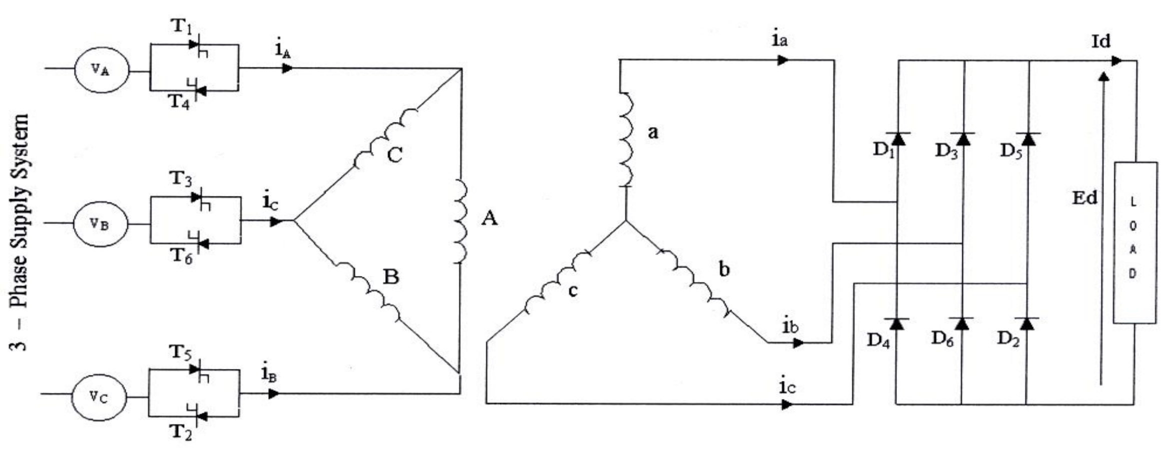


Fig.2 Circuit configuration of ac voltage regulator with 3-phase bridge rectifier.

$$\left.\begin{aligned} V_A &= \sqrt{2}\, E_n \sin(\omega t) \\ V_B &= \sqrt{2}\, E_n \sin(\omega t - 2\frac{\pi}{3}) \\ V_C &= \sqrt{2}\, E_n \sin(\omega t - 4\frac{\pi}{3}) \end{aligned}\right\} \quad (18)$$

The corresponding line-to-line supply voltage be:

$$\left.\begin{aligned} V_{AB} &= \sqrt{6}\, E_n \sin(\omega t + \frac{\pi}{6}) \\ V_{BC} &= \sqrt{6}\, E_n \sin(\omega t - \frac{\pi}{2}) \\ V_{CA} &= \sqrt{6}\, E_n \sin(\omega t - \frac{7\pi}{6}) \end{aligned}\right\} \quad (19)$$

The operation of this model of AC\DC converter is depends on the firing angle values. 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 = π \ 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. For the range of α , $30^{o^\circ} \le \alpha \le 60^{\circ o}$, there are certain periods when three thyristors conduct and another when two thyristors conduct simultaneously. This particular mode of operation is represented the notation mode 2\3. 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. This operation of the circuit describe as mode 2\2 , extends over the firing angle rang from 60^o to 90^o . Last mode of operation is referred to as mode 0\2 describe the operation for firing angle rang from 90^o to 150^o which discontinuous condition is occur. **Fig.3** shows the waveforms of secondary and supply line currents for different modes of operation .

* CALCULATION OF DISPLACEMENT FACTOR, DISTORTION FACTOR AND TOTAL POWER FACTOR

The displacement, distortion and total power factor at the supply side can be evaluated in terms of Fourier coefficients . The displacement factor can be found by using Eq.(15) and the Fourier coefficients and given by:

$$\cos\phi_1 = \begin{cases} 1 & \alpha \le 30^\circ \\ \dfrac{(4\pi - 6\alpha \div 3Sin2\alpha)}{\left[9(1-\cos(2\alpha))^2 + \langle 4\pi - 6\alpha + 3\sin(2\alpha)\rangle^2\right]^{1/2}} & 30^o \le \alpha \le 60^\circ \\ \dfrac{2\pi + 3\sqrt{3}\cos 2(\alpha - 30^o)}{\left[27 + 4\pi^2 + 12\sqrt{3}\,\pi\cos 2(\alpha - 30^o)\right]^{1/2}} & 60^o \le \alpha \le 90^\circ \\ \dfrac{5\pi - 6\alpha - 3\sin 2(\alpha - 60^o)}{\left[9(1+\cos(2\alpha - 60^\circ))^2 + \langle 5\pi - 6\alpha - 3\sin 2(\alpha - 60^o)\rangle^2\right]^{1/2}} & 90^\circ \le \alpha \le 150^\circ \end{cases} \tag{20}$$

By Combination of Eq. (1) and the Fourier coefficients ,results in the following expression for distortion factor:

$$\cos\,\delta = \begin{cases} \left[\dfrac{2\pi + 3\sqrt{3}\cos 2\alpha}{4\pi}\right]^{1/2} & \alpha \le 30^\circ \\ \left[\dfrac{\left[9(1-\cos(2\alpha))^2 + \langle 4\pi - 6\alpha + 3\sin(2\alpha)\rangle^2\right]}{4\pi(4\pi - 5\pi \div 3Sin2\alpha)}\right]^{1/2} & 30^o \le \alpha \le 60^\circ \\ \left[\dfrac{(27 + 4\pi^2 + 12\sqrt{3}\,\pi\cos 2(\alpha - 30^o))}{4\pi(2\pi + 3\sqrt{3}\cos 2(\alpha - 30^o))}\right]^{1/2} & 60^\circ \le \alpha \le 90^\circ \\ \left[\dfrac{9(1+\cos(2\alpha - 60^\circ))^2 + \langle 5\pi - 6\alpha - 3\sin 2(\alpha - 60^o)\rangle^2}{4\pi\langle 5\pi - 6\alpha - 3\sin 2(\alpha - 60^o)\rangle}\right] & 90^\circ \le \alpha \le 150^\circ \end{cases} \tag{21}$$

The supply total power factor is obtained by using Eq. (14), or can be expressed as the product of Eq. (20) and (21) and given by:

$$PF = \begin{cases} \left[\dfrac{2\pi + 3\sqrt{3}}{4\pi}\right]^{1/2} & \alpha \le 30^\circ \\ \left[\dfrac{(4\pi - 6\alpha \div 3Sin2\alpha)}{4\pi}\right]^{1/2} & 30^o \le \alpha \le 60^\circ \\ \left[\dfrac{2\pi + 3\sqrt{3}\cos 2(\alpha - 30^o)}{4\pi}\right]^{1/2} & 60^o \le \alpha \le 90^\circ \\ \left[\dfrac{5\pi - 6\alpha - 3\sin 2(\alpha - 60^o)}{4\pi}\right]^{1/2} & 90^\circ \le \alpha \le 150^\circ \end{cases} \tag{22}$$

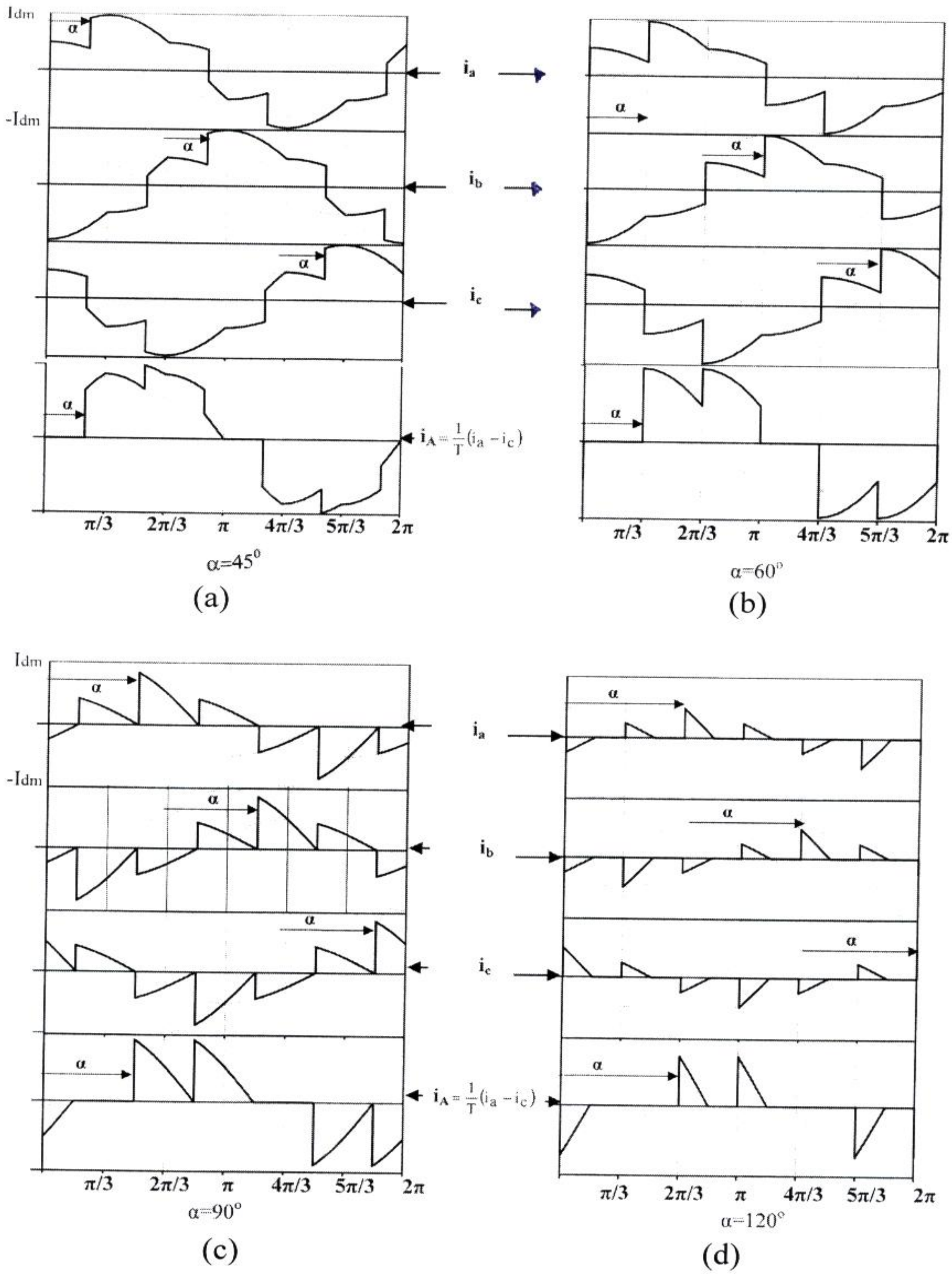


Fig.3 Secondary and supply line currents for different firing angles.

- 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.).

A 3-phase , 6-pulse , 4.2 Kw is assembled and connected to 0.4 Kv power supply through 3-phase , ac voltage regulator (fig.(2)). The driver input signal to the firing circuit is in the range (0-6.3) which provides a firing angles from zero to150^o . 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.3 shows the experimental waveform of the supply line current and the corresponding frequency spectrum. The displacement, distortion and total power factors computed by tow simulation methods and these results and the experimental results are shown in **Fig.4** – **Fig.6**. Form **Fig.4** , it can be seen that the displacement factor has a maximum value of 0.94 at uncontrolled region ($\alpha \leq 30^o$) . This is due to the supply current is approximately in phase with the supply phase voltage. With firing angle increases the displacement factor is rabidly decrease because the firing angle shifts the supply current waveform and this increase the displacement angle , hence , decrease the displacement factor.

The changes in the distortion factor values with the increase of the firing angles are small as shown in **Fig.5**. For firing angle greater than 70^o , the harmonic currents begin to effect the values of distortion factor and this affect increases as the firing angle increases. The distortion factor is equals to 0.932 at $\alpha = 70^o$ and decrease to 0.812 at firing angle equals to 110^o . Also , the fundamental component of experimental results is found to be greater than the theoretical results , especially at higher firing angles, and this explain the reason of significant reduction in the distortion factor of the experimental results. From **Fig.6** , the maximum total power factor is 0.914 which is measured at no control angle and reaches zero at $\alpha = 150^o$.

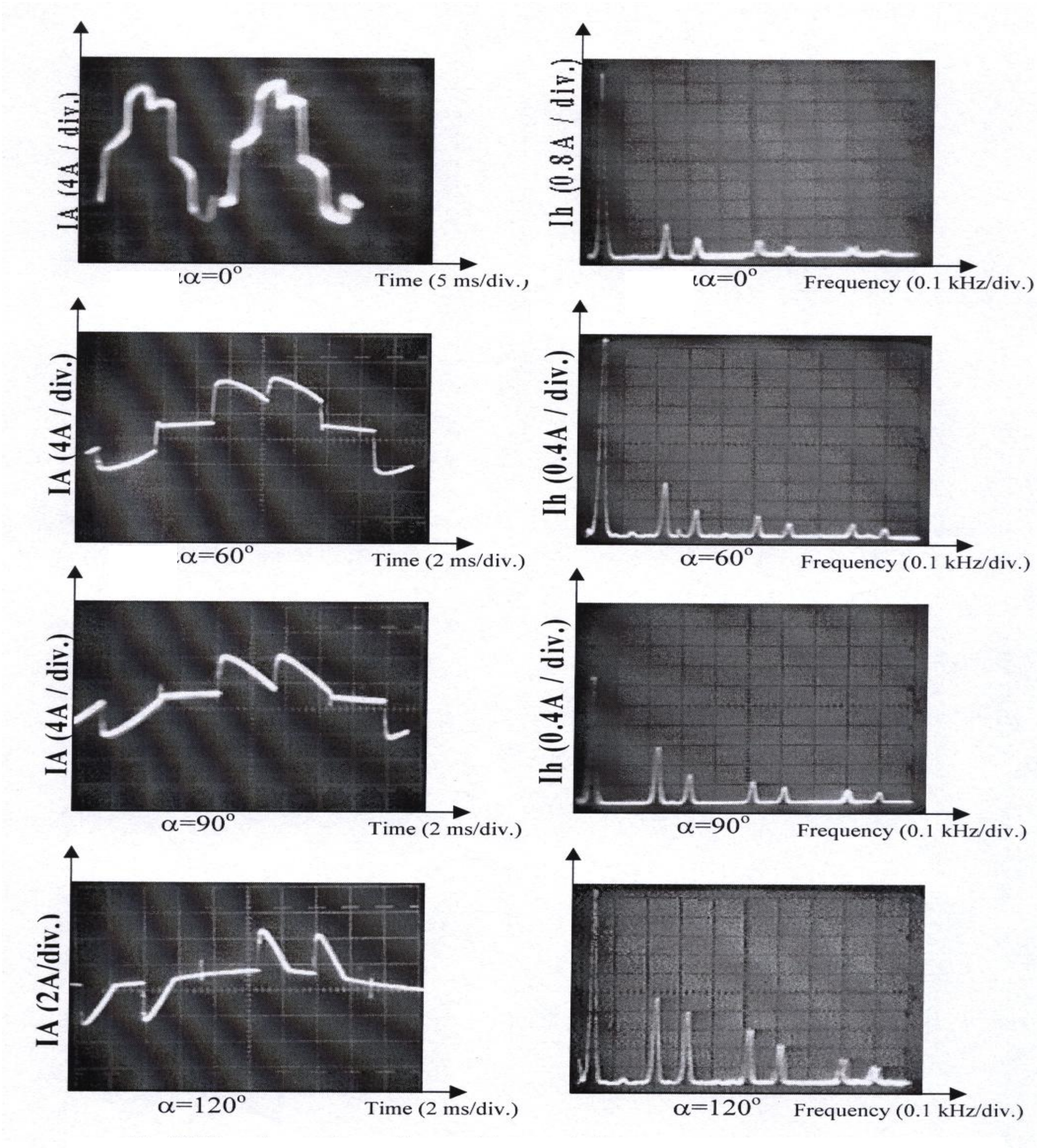


Fig.3 Experimental waveforms of the supply line current and corresponding frequency spectrum.

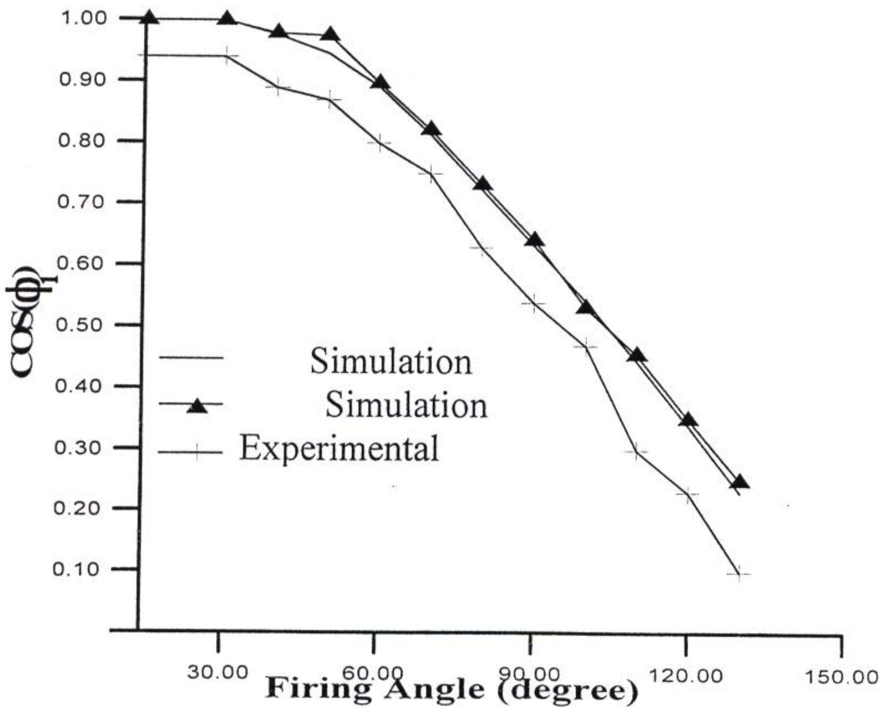


Fig.4 Simulation and experimental results of displacement factor.

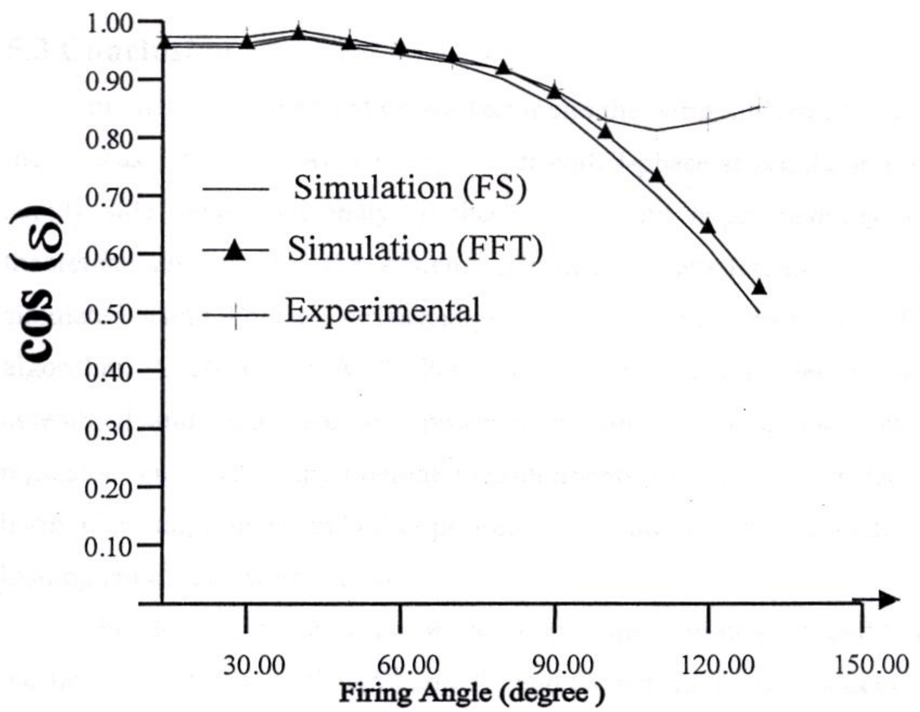


Fig.(5) Simulation and experimental results of distortion factor.

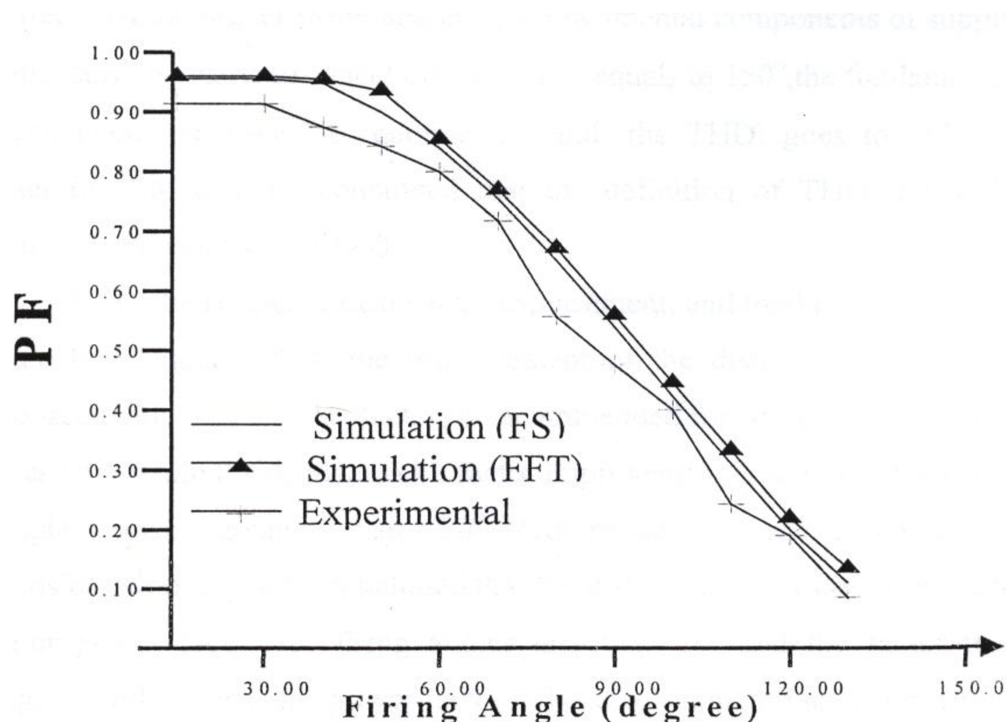


Fig.(6) Simulation and experimental results of power factor.

CONCLUSION

In this paper , the total power factor of the 3-phase, 6-pulse , ac\dc converter with 3-phase ac voltage regulator at the supply side is analyzed theoretically and experimentally. The theoretical analysis for the harmonic current , and total power factor are 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 harmonics amplitudes, total power factor and other parameters were carried out. From the results of distortion factor , displacement factor and total power factor it can be deduce that the agreement between experimental and simulation results is fair but there are small differences between them . This is because of commutation effect , errors in measuring exactly the values of firing angle , and the instrument inaccuracies. The improvement of the distortion factor , and consequently the power factor , is recommended for firing angle greater than 70^o , while the displacement factor improvement is required for firing angle greater than 30^o. From above consideration , it can be concluded that the distortion factor does not cause poor power factor for firing angle less than $70^o$and the factor that significantly effects the power factor is the displacement factor. For firing angle greater than 70^o , both the distortion and displacement factors are responsible of lower power factor.

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.

REFERENCES

- H. Mao , etal , 1997," Review of high performance three phase power factor correction circuits" , IEEE Trans. On Industry electronics , Vol.44 , No. 4 , Aug., PP 437-445.

- IEEE standard 519 – 1992 , 1993, " IEEE recommended practices and requirements for harmonic control in electrical power systems" .

- J. Arrillaga , et al , 1997 " Power system harmonic analysis " , London: Wiley.

- L. Cividino , 1992 , " Power factor , harmonics distortion , causes , effects and considerations " 14'th international conference on telecommunication energy , Oct. , pp. 506 – 513.

- P. Filipski S.,1991 , " Polyphase apperent power and power factor under distorted wavevorme condition " , IEEE Trans. On Power Delivery , Vol.6 , No. 3 , July, PP 1161-1165.

- R. D. Henderson and P. J. Rose , 1994, " Harmonics: the effect on power quality and transformer " , IEEE Trans. On Industry Applications , Vol.30 , No. 3 , May\June, PP 528-532.

- Task Force on Harmonics Modeling and Simulation , 1996 , "modeling and simulation of the propagation of harmonics in electric power networks " , IEEE Trans. On Power delivery , Vol.11 , No. 1, Jan. ,PP 452-461.

- V. K. Mehta , 1998 ," Principle of power system " , S. Chand and Company ltd. , India .

- W. Shepherd and P. Zand , 1979, "Energy flow and power factor in nonsinusoidal circuits " , Cambridge university press .

- Y. Jang and M. Jovanovic, 1998 , " A comparative study of single switch , three phase , high power factor rectifier ", IEEE APEC'98 Conference record , part 2 , PP 1093-1099.

LIST OF SYMBOLS

α = Firing angle.

Cos φ_1 = displacement factor.

Cos δ = Distortion factor.

D = distortion power.

Ed = Average direct voltage.

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

h = order of harmonic.

i (ωt) = Instantaneous supply current.

I_d = Average value of dc load current.

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

I_l = fundamental component of $I_{L.}$

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

IL = supply line current (rms).

K = Integer no. , 1,2 ,3 , …

P = Active input power.

PF = total power factor.

R = Resistance of dc load.

S = Total apparent power.

S_1 = fundamental component of apparent power.

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.