Ibekwe B.E. et al. Int. Journal of Engineering Research and Applications www.ijera.com
ISSN : 2248-9622, Vol. 4, Issue 10(Part - 4), October 2014, pp.50-61

RESEARCH ARTICLE OPEN ACCESS

Guiding Principles in Selecting AC To DC Converters For Power Factor Corrections in AC Transmission System

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ABSTRACT:
The ac to dc converters' power factors correction in ac transmission system were investigated. The studies include: phase-controlled converter; pulse width modulated (PWM) converter and ac input current shaped converter. Using Fourier series, power factors of these converters were calculated and simulated using MATLAB. The resulting curves are displayed in the hard copies for practical guides in the choice of converters; and comparatively, current shaped type is the best.

Keywords*:* ac to dc converters, ac transmission lines, current-shaping converters, PF corrections, PWM converters,

I. INTRODUCTION

The presence of low frequency current harmonics have brought about so many problems in power system such as voltage distortion, limitations in the amount of available power, heating in ac mains to mention but a few. These not withstanding, however, the growing demand for electrical power has continued to assume increasing dimensions on daily basis resulting increasing number of nonlinear loads in the utilities [1]. This paper aims at addressing this problem by selecting appropriate ac to dc converter types in ac transmission system. The topic intends to analyse the various power factor improvement techniques in ac to dc converters with a view to adopting at a glance, the available options for various power applications and uses to meet all professional utility power signal distortion levels [2].

The paper concerned with ac input power factor for static ac to dc converters and its improvement techniques is carried out on the following converter types [3]

1) Phase – controlled ac to dc converter
2) Voltage pulse – width modulated (PWM) ac to dc converters.
3) Ac to dc converters with ac input current shaping.

Power factor correction is a way of counteracting the undesirable effects of eclectic load that create a power factor less than unity [4]. Electric load in alternating current require apparent power which is made up of real power plus reactive power. Real power is the power consumed by the load, while reactive power is the power repeatedly demanded by the load but is returned to the source; and it is the cyclic effect that occurs when alternating current passes through a load containing reactive components.

The knowledge of ac input power factor characteristics of various ac to dc converter [4] will enable the practicing engineers to select appropriate ac to dc converter types for specified applications in a given level of nonlinear loads present in a utility system. With the increasing application of static switched converters for controlled industrial power supplies, the non-sinusoidal utility line current being drawn by these converters which essentially constitute the nonlinear load in the system has been rapidly increasing [5]. The non-sinusoidal current contains harmonics which not only give rise to poor ac input power factor to the nonlinear loads but also constitute level interference to communication lines [5].

Reactive power in the system is responsible for real power being less than the apparent power, and this brings about the power loss between transmission and distribution systems. This in turn brings about huge operational and financial loss to the power companies.

The PWM technique has the advantage of maintaining the ac input power factor at unity while flywheeling method improves the overall ac input power factor, but the ac input power factor still decrease with decrease in the load voltage. Therefore both phase control with control flywheeling and the PWM method are tolerable where nonlinear load concentration is low. For locations (especially industrial) where nonlinear load concentration is high, current PWM power factor correction method is essentially the only method to keep the injected harmonics into the utility line below the maximum tolerable level. If these checks are not taken seriously, the power companies will try to step in to prevail on their customers, especially those with large electric loads to maintain their power factors above certain amounts (0.9 and above) or be subject to extra charges. They however give bonuses and incentives to customers that comply with them.

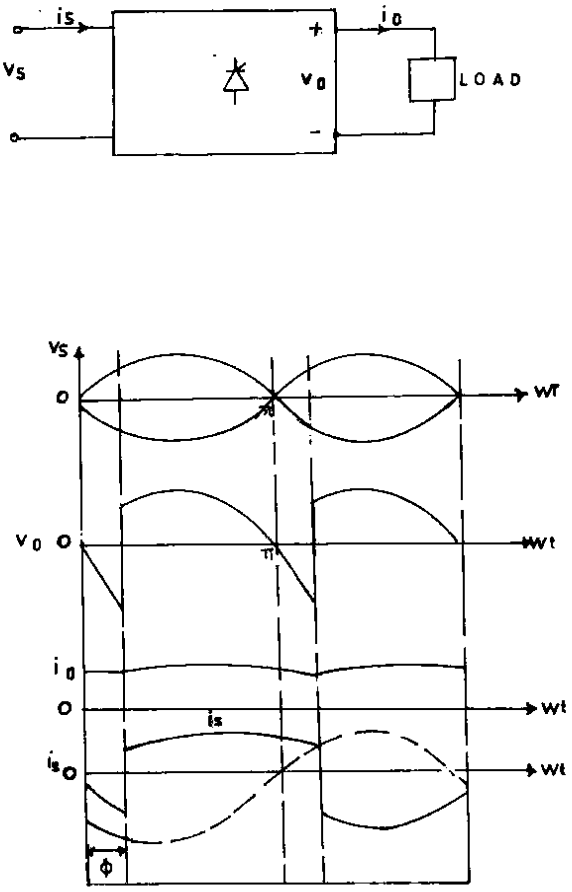
Now as the detailed power factor study for all the above mentioned power factor improvement or correction techniques were carried out, to solve the problems of nonlinear loads present in the system by static ac to dc converter (switched or non-switched), many proposals were made. The first proposal is to reduce converter ac input harmonic distortion level by preventing the load voltage from reversing [9].

This is achieved by a predetermined active converter switch control/or the introduction of a free-wheeling diode across the converter output load. The effect is improvement of the ac input power factor to values higher than those of the fully phase controlled converter over certain load variation range. The next strategy to achieve power factor improvement is by pulse width modulation of the converter output voltage for various forms of the ac to dc converters [10]

Now we explain them one by one with their calculated power factors, as follows:

II. PHASE CONTROLLED AC TO DC CONVERTERS

Phase control has to do with the varying of the firing angle of the converter semi-conductor devices in order to obtain power control [7]. Fig. 2.1(a) represents the generalized ac to dc converter while (b) represents the voltage and current waveforms. In ac to dc converters diodes or thyristors are principally employed in the conversion when phase control is involved. But when pulse width modulation (PWM) control is to be employed, transistors such as Bipolar Junction Transistors (BJT) and metal oxide semi-field effect transistors (MOSFET) [6] are preferred.



Flg.2.1: (a) Generalized ac to dc converter
(b) The voltage and current waveforms.

2.1 CALCULATED POWER FACTORS

Under the single-phase we have:

a) Single-phase full bridge two-pulse and the calculated power factor (P.F.) is

$$P_{FAC} = \frac{2\sqrt{2}}{\pi}\cos\alpha \tag{2.1}$$

b) Single-phase full bridge with controlled fly-wheeling and the calculated power factor (P.F) is

$$P_{FAC} = \frac{2\sqrt{2}\cos^2\left(\frac{\alpha_p}{2}\right)}{\sqrt{\pi(\pi-\alpha)}} \tag{2.2}$$

And for the three phase category we have:

a) Three-phase full bridge six-pulse with the calculated power factor (P.F.) as,

$$P_{FAC} = \frac{3}{\pi}\cos\alpha \tag{2.3}$$

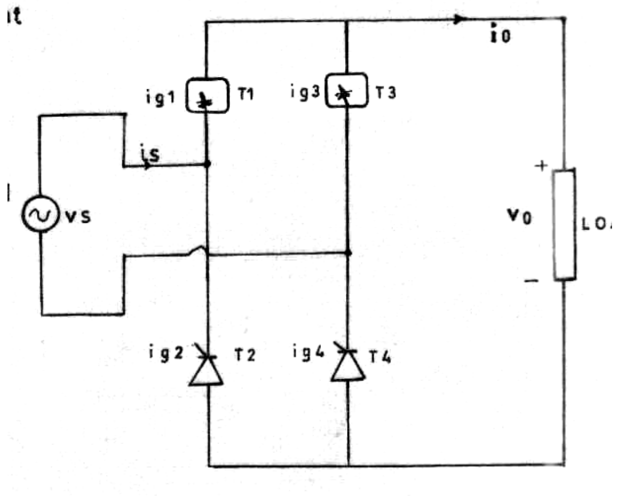
b) Three-phase full bridge with controlled fly-wheeling and the power factor calculated as

$$P_{FAC} = \frac{3}{\pi}\cos^2\left(\frac{\alpha_p}{2}\right) \tag{2.4}$$

Where in all cases α and or α_p = phase angle difference

III. VOLTAGE PULSE WIDTH MODULATION METHOD (P.W.M.) AC TO DC CONVERTER

Pulse width modulation (P.W.M) by definition is a method of varying the mark-to-space ratio of the output voltage waveform during a cycle so as to minimize the magnitude of the harmonics in the output. It consists of two types viz: single-phase and three-phase P.W.M. Figure 3.1 is the diagram showing single phase pulse width modulated controlled rectifier circuit and its waveform for rectification mode.



(a)

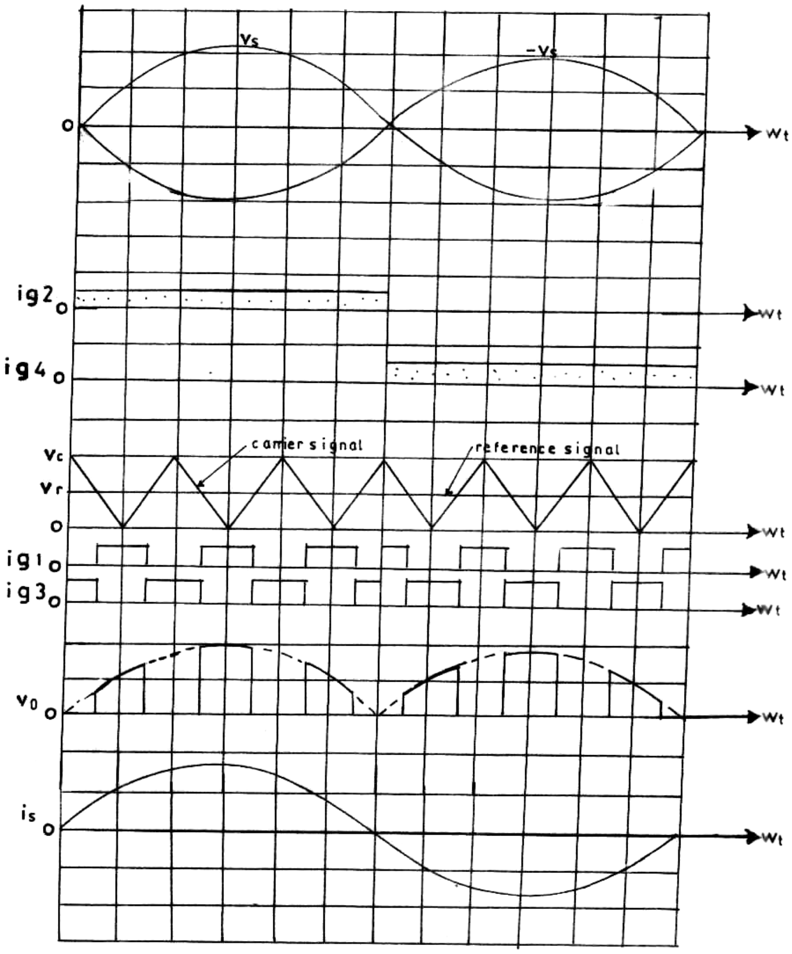


Fig. 3.1 (a) Single-phase PWM fully controlled rectifier circuit (b) Its wave form for rectification mode ($f_c = 6f_s$).

3.1 CALCULATED POWER FACTOR

For single phase P.W.M. method, the calculated power factor is given as:

$$\text{P.F.} = \frac{\sum(\cos\alpha_k - \cos\beta_k)}{\{\sum_{n=1}^{\infty}[\sum_{k=1}^{Np/2} \frac{1}{n}(\cos n\alpha_k - \cos n\beta_k]^2\}^{1/2}} \qquad (3.1)$$

Where P.F. = Power Factor and

NP = Pulse Number (αk, βk) and k are variables with range K($1 \le K \le 2$)

For three phase counterpart, the calculated power factor is:

$$\text{P.F.} = \frac{\sum_{k=1}^{2}(\cos\alpha_k - \cos\beta_k) + \cos\alpha_k}{\left[\sum_{n=1}^{\alpha}\left\{\frac{1}{n}\left[\sum_{2=1}^{2}(\cos n\alpha_k - \cos n\beta_k) + \cos n\alpha_k\right]\right\}^2\right]^{1/2}} \qquad (3.2)$$

Where P.F. = Power Factor

$$\alpha_k = \alpha_0 - \frac{m\sin\alpha_0 + (12/\pi)\alpha_0 + (4k-2)}{m\cos\alpha_0 + 12/\pi}$$

α_k = β_k = rough values of alpha and beta obtained graphically

m = modulation index, range m($0 \le m \le 1$)

k = variable with range k ($1 \le k \le 3$)

n = harmonic order, range n = 1,3,5 ………∞

and where $$\beta_k = \beta_0 - \frac{m\sin\beta_0 + (12/\pi)\beta_0 + (4k-2)}{m\cos\beta_0 + 12/\pi} \qquad (3.3)$$

IV. CURRENT CONTROLLED PULSE WIDTH MODULATION (C.P.W.M) CONSTANT SWITCHING METHOD (SINGLE-PHASE)

The objective research/effort here is to subject the boost converters to constant switching process by switching on and off two diagonally opposite MOSFET key pairs; and using certain circuit configurations the results were solved in Runge-Kutta to obtain the analysis result shown in subsection 5.1. Figure 4.1 is the diagram showing the first circuit configuration of the boost converter with a resistive load while figure 4.2 is the second configuration with a battery load.

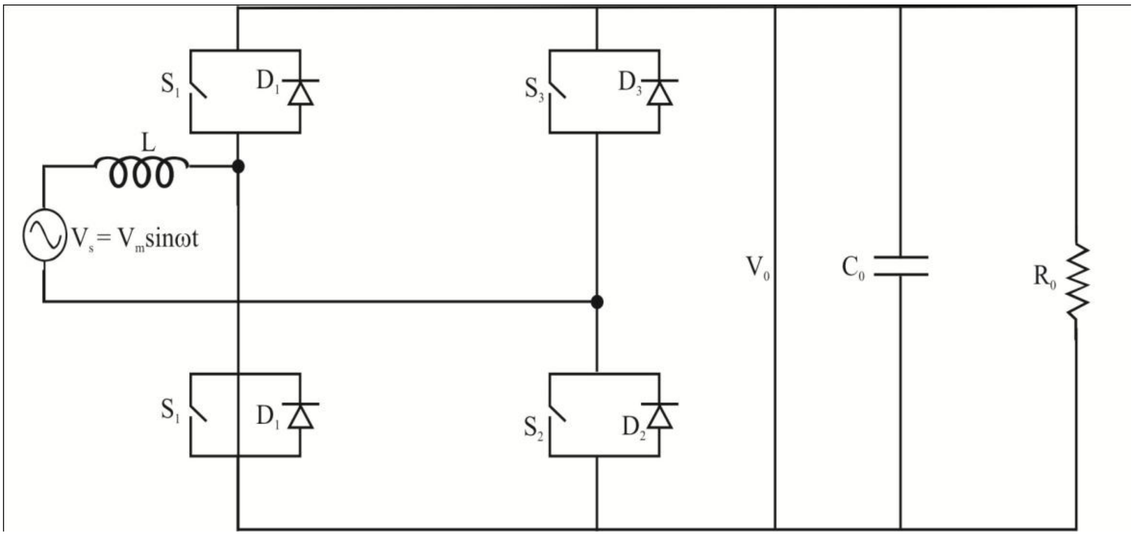


Fig 4.1: with a resistive load

Analysis of Fig. 4.1

(a) S_1S_2 closed (current decreasing):

Current loop: $V_S \to L - D_1 \to V_O \to D_2 \to V_S$

Equation:

$$V_S - L\frac{dis}{dt} - V_O = 0$$

$$\frac{dis}{dt} = \frac{1}{L}\left[V_S - V_O\right]$$

$$= \frac{1}{L}\left[V_m \sin\omega t - V_O\right] \qquad \ldots\ldots\ldots\ldots \qquad (4.1)$$

Again,

$$i_C = C_O d\frac{V_O}{dt}$$

$$i_R = \frac{V_O}{R}$$

$$i_s = i_C + i_R = C_O d\frac{V_O}{dt} + \frac{V_O}{R} = 0$$

$$\therefore \quad \frac{dV_O}{dt} = \frac{1}{C_O}\left[is - \frac{V_O}{R}\right] \qquad \ldots\ldots \qquad (4.2)$$

(b) S_3S_4 closed (current increasing):
Current loop: $V_S \rightarrow L - D_4 \rightarrow V_O \rightarrow D_3 \rightarrow V_S$
Equation:

$$V_S - L\frac{dis}{dt} + V_O = 0$$

$$\frac{dis}{dt} = {}^{1}\!/_{L}\left[V_S + V_O\right]$$

$$= {}^{1}\!/_{L}\left[V_m \sin\omega t + V_O\right] \qquad \ldots\ldots\ldots\ldots \qquad (4.3)$$

Again, $i_C = C_O\frac{dV_O}{dt}$

$$i_R = \frac{V_O}{R}$$

$$i_s = -i_C - i_R$$

$$i_s = -C_O\frac{dV_O}{dt} - \frac{V_O}{R}$$

$$i_s + C_O\frac{dV_O}{dt} + \frac{V_O}{R} = 0$$

$$i_s + \frac{V_O}{R} = -C_O\frac{dV_O}{dt}$$

$$\frac{1}{C_O}\left[is + \frac{V_O}{R}\right] = -\frac{dV_O}{dt}$$

$$-\frac{1}{C_O}\left[is + \frac{V_O}{R}\right] = \frac{dV_O}{dt}$$

$$\therefore \quad \frac{dV_O}{dt} = -\frac{1}{C_O}\left[is + \frac{V_O}{R}\right] \qquad \ldots\ldots\ldots \quad (4.4)$$

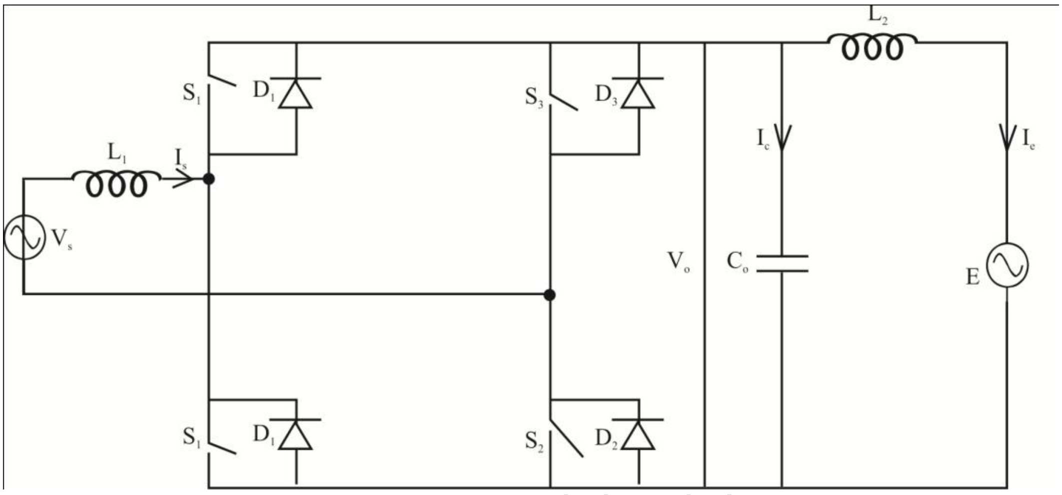


Fig 4.2: Circuit 2 with a battery load

ANALYSIS OF CIRCUIT 2

(a) S_1S_2 closed
Current loop: $V_S \rightarrow L_1 - D_1 \rightarrow V_O \rightarrow D_2 \rightarrow V_S$
Equation:

$$V_S - L_1\left(\frac{dis}{dt}\right) - V_O = 0$$

$$\frac{dis}{dt} = {(V_S - V_O)}\big/{L_1} \qquad \ldots\ldots\ldots \quad (4.5)$$

$$i_s = i_c + i_e$$

$$i_s = C_O\left(\frac{dV_O}{dt}\right) + i_e$$

$$\frac{dV_O}{dt} = {(i_s - i_e)}\big/{C_O} \qquad \ldots\ldots\ldots\ldots \quad (4.6)$$

Again 2nd loop:

$$V_O - L_2\left(\frac{die}{dt}\right) + E = 0$$

$$\frac{die}{dt} = {(V_O + E)}\big/{L_2} \qquad \ldots\ldots\ldots\ldots \quad (4.7)$$

(b) S_3S_4 closed

Current loop: $V_S \rightarrow L_1 - D_4 \rightarrow V_O \rightarrow D_3 \rightarrow V_S$

Equation:

$$V_S - L_1\left(\frac{dis}{dt}\right) + V_O = 0$$

$$\frac{dis}{dt} = {(V_S + V_O)}\big/{L_1} \qquad \ldots\ldots\ldots \quad (4.8)$$

$$i_s = -i_c - i_e$$

$$i_s = -C_O\left(\frac{dV_O}{dt}\right) - i_e$$

$$\frac{dV_O}{dt} = -{(i_s - i_e)}\big/{C_O} \qquad \ldots\ldots\ldots\ldots \quad (4.9)$$

Again 2nd loop:

$$V_O + L_2\left(\frac{die}{dt}\right) + E = 0$$

$$\frac{die}{dt} = -{(V_O + E)}\big/{L_2} \qquad \ldots\ldots\ldots\ldots \quad (4.10)$$

LOAD ANALYSIS:

The circuit equations were loaded with the parameters defined below:

$V_S = 220\sqrt{2}$, wt = 2π; switching period 4KHz. Assume ac and dc input power filters as L = 5mH, C = 0.6F and load resistance, R = 20Ω. The four equations were solved in MATLAB using Runge – Kutta as shown in the work programs at the appendix; hence the plot of the output voltage and current waveforms are shown in Figs. 5.3 and 5.4 of the analysis result.

ANALYSIS RESULTS

5.1 SINGLE PHASE, PHASE CONTROL

Plots (1) and (2) of fig. 5.1 are the results of the phase controlled single phase full bridge two pulse of equation (2.1) and single phase full bridge with controlled flywheeling of equation (2.2); while plot (3) is the simulated curve from equation (3.1), the single phase full bridge P.W.M. All the work programs (in MATLAB) from where all these curves were generated are as shown in the appendix.

Fig.5.1: Computer simulated curves for phase control: (1) single phase full bridge two pulse, (2) single phase full bridge fly wheeling and (3) single phase full bridge P.W.M.

5.2 THREE-PHASE, PHASE CONTROL

Plots (1) and (2) are for the results of phase controlled three phase full bridge six pulse with P.F. expression in equation (2.3) and that of he three phase controlled flywheeling, P.F. expression in equation (2.4) respectively. Plot (3) is the simulated curve from the three-phase P.W.M. P.F. expression in equation (3.2). In all cases, the work program in MATLAB from where all these curves were generated are as shown in the appendix.

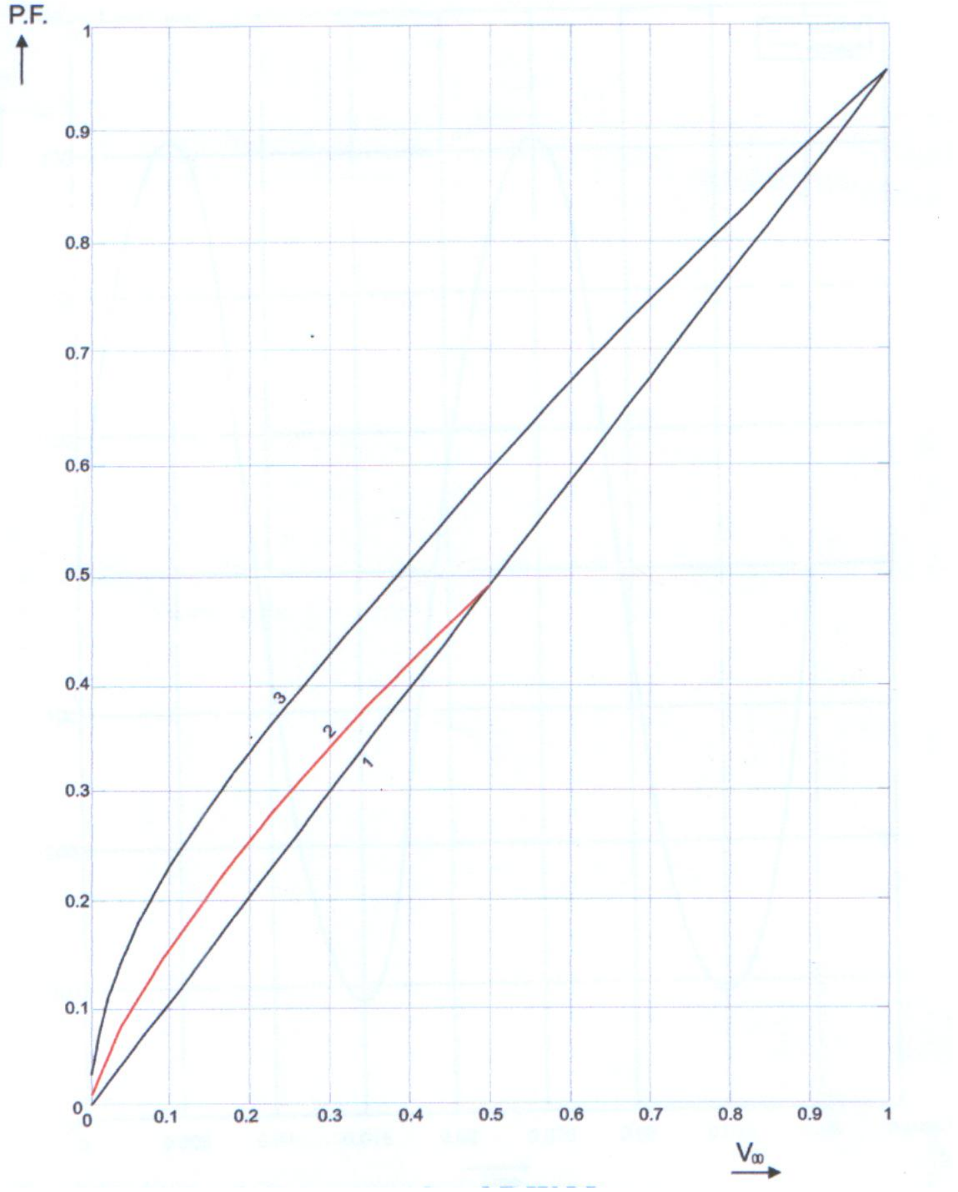


Fig. 5.2 (3) Three-phase full bridge P. W.M. Curves, (2) Three-phase full bridge with controlled fly-wheeling curves and (3) Three-phase full bridge six pulse curve

5.3 CURRENT - PULSE WIDTH MODULATION METHOD

The computer simulated curves of fig (5.3) and (5.4) are the results obtained by using certain circuit configurations of the boost converters as described in section (4). In both cases the MATLAB work programs from where the curves were generated are as shown in the appendix.

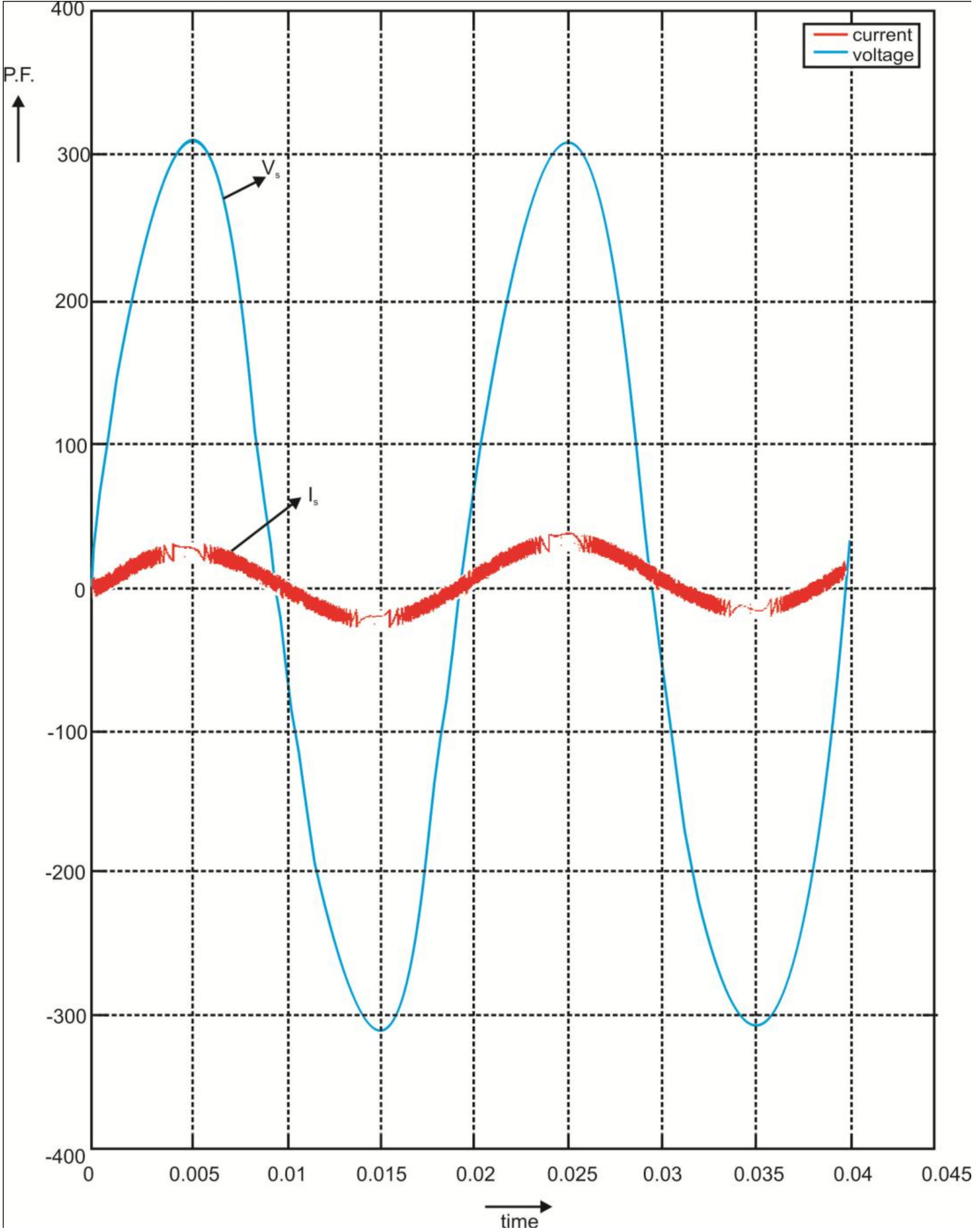


Fig.5.3 Computer Simulated Curve for the Circuit Configuration [1]

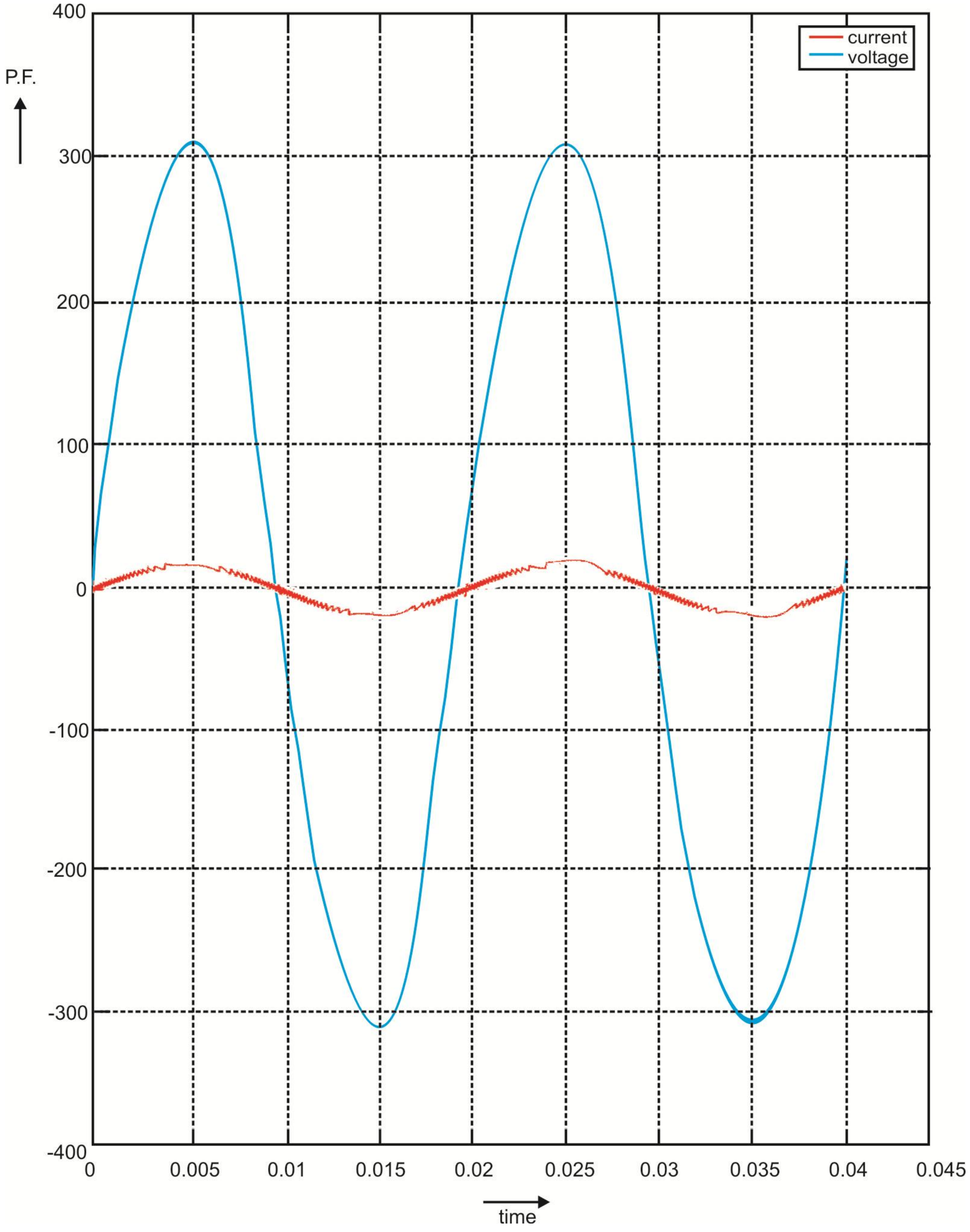


Fig. 5.4: Computer Simulated Curve for the Circuit Configuration [2]

5.4 COMMENTS ON THE ANALYSIS RESULTS

Since harmonics decrease with the increase of rectifiers pulse numbers, the three-phase-six-pulse rectifiers have lower amplitude of harmonics than the single-phase-two-pulse rectifiers, and therefore have a better power factor. Again, from the analysis results, it can be seen that voltage P.W.M. curves (3) in figs. 5.1 and 5.2 have shown remarkable improvement of the power factors over the controlled flywheeling curves (2) and phase control curves (1). However, in both cases the a.c. input power factor degenerate with decrease in load voltage and therefore have poor output powers. They are recommended for places where the nonlinear load concentration is low. For locations with higher concentration of nonlinear loads such as industrial, current P.W.M. where the a.c input current is in phase with the voltage is the best. This improves the power factor to about 98%.

5.5 CONCLUSION

In conclusion, all phase-controlled converters and voltage-controlled P.W.M. converters are recommended for use in locations with low non-linear load concentrations, while for industrial locations with higher non-linear loads, current P.W.M is best recommended.

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