The Input Power Factor Problem of Industrial Drives

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Abstract
This paper presents the a.c input power factor problem of an Industrial drive connected to a DC motor load and operated either in the continuous or discontinuous inductor current mode. An in-depth mathematical analysis of the drive system and its behavior factors: Harmonic factor (HF), Displacement factor (DF), Power factor (PF) etc is also discussed to provide users with limited knowledge of the drive.
Keywords: Drives, Power Factor, Harmonic Factor, Displacement Factor.
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1.0 INTRODUCTION

With the re – awakening of the long abandoned Ajaokuta Steel Rolling mills, Aluminum Smelting plant at Ikot – Abasi, Aladja Steel rolling mills, a large number of converters are expected to be in use. Also, the development of many kilometers of rails from Aladja, following the immediate take off of the Ajaokuta Steel Mills and associated industrialization in the steel sector is expected to increase the harmonic currents produced by drives in Power Generating, Transmission and Distribution Company of Nigeria network and hence will bring the associated problems to the fore (Okoro, 1982; Osunde 2012).

According to Sen (1981), Agu (1997), Zander (1973) and Muhammed (1993), Industrial drives connected to an electricity distribution network introduce non - sinusoidal waveforms at the ac input side as a result of the switching action of the devices. It also produces a non – sinusoidal line current due to the non – linear input characteristics. With the steadily increasing use of such drives, line current harmonics have become a significant problem. Their adverse effects on the power system are well recognized (Okoro 1985, Fuhao 1974).

Okoro (1987), Ira et al (1997), in their study reveals that the presence of harmonics in the supply waveforms has a wide – ranging effects on the supply system. These include:

- Degradation of system voltage waveforms and of equipment performance and effective life.
- Overheating in transformers and induction motors, shunt capacitors, power cables, electrical machines and switchgear leading to premature ageing.
- Increased transmission losses, protective system mal – operation, communication system interference and above all
- Poor input power factor (Sapna and Vijay 2013)

These reports (Aparna and Umesh 2015) were influenced by the identified interest in the many factors that affect the magnitude of the ripple fed to the controlled machine and their impact on the overall performance of the drives. To clearly present this problem, the single – phase asymmetrical bridge converter has been chosen as a peculiar drive for the analysis because it

has a wide range of application and presents the worst form of harmonics (Okoro 1993, Mehta 1974). Fourier series has been employed to gain understanding of the basic operation and behaviour of a typical Single – Phase Asymmetrical Bridge Converter Controller.

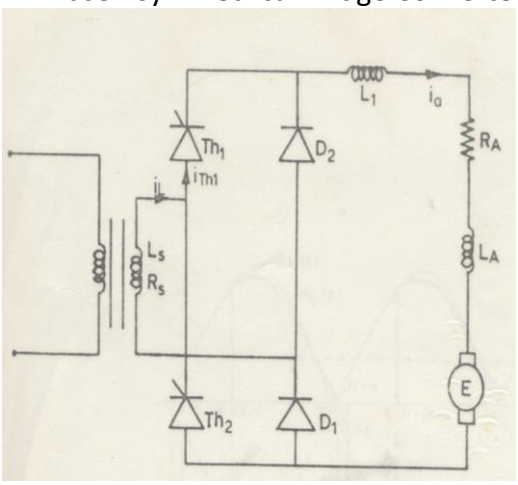


Figure 1: The Asymmetrical Bridge Converter.

2.0 METHODOLOGY

2.1 Analysis of the Asymmetrical Single –Phase Drive.

2.11 Discontinuous Armature Current Mode

The basic circuit of the asymmetrical single – Phase Bridge shown in Figure 1 has been studied and analyzed in previous work (Okoro 1987, Mehta 1974, Dewan et al 1970 and Sen 1981). The current and voltage waveforms are shown in Figure 2. Explicit expression of the input current can be obtained by analyzing the half – cycle equivalent circuits in Figure 3 for the different intervals assuming that the terminal condition of one interval are the initial conditions for the next interval.

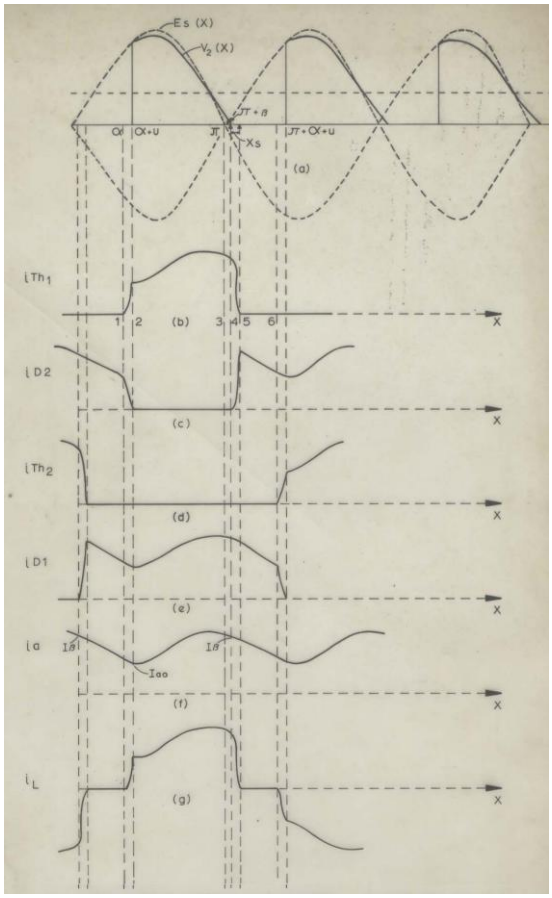


Figure 2: Waveforms of the bridge converter;
(a) Voltage waveforms
(b) – (g) Current waveforms
Operating Intervals:
1 – 2 Forward Commutation of TH_1
2 – 3 Conduction of TH_1
3 – 4 Angle β after π for to become forward biased
4 – 5 Extinction interval
5 – 6 Freewheeling interval

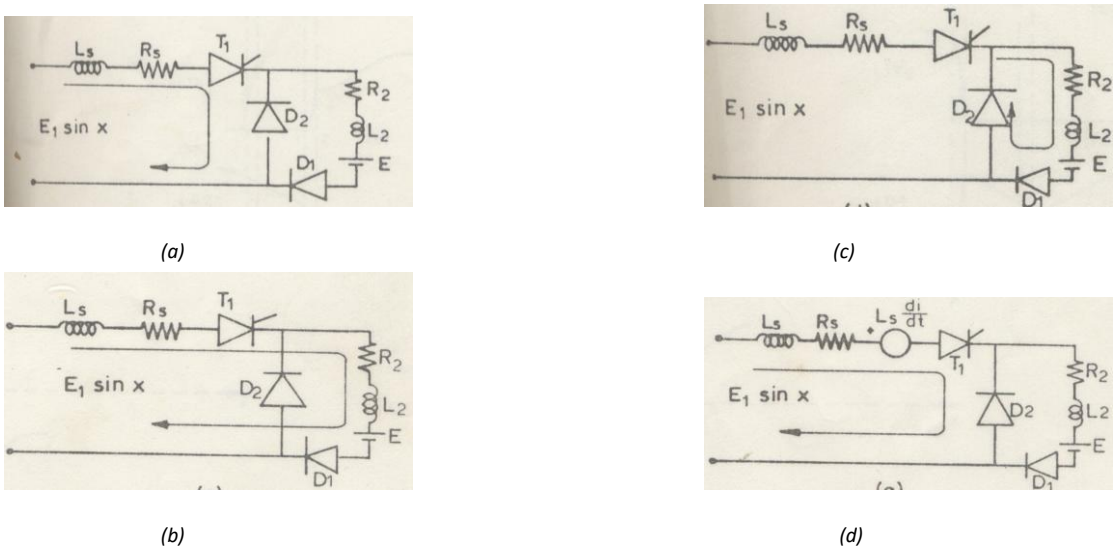


Figure 3: Half circle equivalent circuit showing path of current during different intervals
(a) Forward Commutation interval: $\alpha < x < \alpha + u$
(b) Conduction interval: $\alpha + u < x < \pi$
(c) Freewheeling interval $0 < x < \alpha$
(d) Reverse Commutation or Extinction interval: $\pi + \beta < x < \pi + \beta + x_s$

The simplying equations are based on the following assumptions (Okoro 1982, Sen (1981).

- That the thyristors are ideal switches
- That a steady state condition has been established to justify repeatitive representation of the cycles.
- Non – linearity in operation of the machine is included in the parameters of the system equations.
- That the motor is separately excited.

In the forward commutation interval, $\alpha < x < \alpha + u$, fig. 3(b), before the current in a thyristor gated at delay angle 'α'reaches the value of current in the armature, the equation for the circuit of fig. 3(b) in which the forward commutating current flows is:

$$R_s i + L_s \frac{di}{dt} = E_1 \sin(\omega t + \alpha) \tag{1}$$

With initial condition $i = 0$ at $\omega t = 0$, the current in this interval is given by:

$$i(t) = K_1 \left\{ \sin(\omega t + \alpha - \theta_1) + \sin(\theta_1 - \alpha) \exp\left(\frac{-t}{\tau_1}\right) \right\} \tag{2}$$

Where, $k_1 = \frac{E_1}{Z_1}$, $Z_1 = R_s + j\omega L_s$, $\tau_1 = \frac{L_s}{R_s}$

$$\theta_1 = \tan^{-1} \frac{\omega L_s}{R_s}$$

Current at the end of the interval when $\omega t = u$ is:

$$I_{ao} = K_1\left\{\sin(\omega t + \alpha - \theta_1) + \sin(\theta_1 - \alpha)\exp\left(\frac{-u}{\omega\tau_1}\right)\right\} \quad (3)$$

In the interval $\alpha + u \le x < \pi$, the current flows in the path shown in Fig. 3(b) and is given by the equation,

$$L\frac{di}{dt} + Ri + E = E_1\sin(\omega t + \alpha + u) \quad (4)$$

Where, $L = L_s + L_1 + L_a$, $R = R_s + R_a$

With the initial condition $i = I_{ao}$ at $\omega t = 0$, the current in the interval is:

$$i(x) = K_2\left[\cos\theta_2\ \sin(x - \theta_2) - P\right] + \left\{K_2\left[\cos\theta_2\sin(\theta_2 - \alpha - u) + P\right] + I_{ao}\right\} * \exp\left(-\left(\frac{x - \alpha - u}{\omega t}\right)\right) \quad (5)$$

Where, $K_2 = \frac{E_1}{R}$, $P = \frac{E}{E_1}$, $\theta_2 = \tan^{-1}\frac{\omega L}{R}$

$\tau = \frac{L}{R}$

and, $x = \omega t + \alpha + u$

In the interval $0 < x < \alpha$, the load is not connected to the supply, current flows in the path shown in fig. 3(c) and is given by;

$$L_2\frac{di}{dt} + iR_a = -E \quad (6)$$

Where, $L_2 = L_1 + L_a$

With initial current I_1 at $x = 0$, the current in the free-wheeling interval is;

$$i(x) = I_1\exp\left(\frac{-x}{\omega\tau_2}\right) - \left(\frac{E}{R_a}\right)\left(1 - \exp\left(\frac{-x}{\omega\tau_2}\right)\right) \quad (7)$$

Where, $\tau_2 = \frac{L_2}{R_a}$

At $x = \alpha + u$, the current is I_{ao}, which is given by the equation;

$$I_{ao} = I_1\exp\left(\frac{-(\alpha + u)}{\omega\tau_2}\right) - \left(\frac{E}{R_a}\right)\left(1 - \exp\left(\frac{-(\alpha + u)}{\omega\tau_2}\right)\right) \quad (8)$$

Combining equations (3) and (8), gives the current at $x = 0$ as;

$$I_1 = \left[\begin{matrix} K_1\left\{\sin(u + \alpha - \theta_1) + \sin(\theta_1 - \alpha)\exp\left(\frac{-u}{\omega\tau_1}\right)\right\} + \\ \frac{E}{R_a}\end{matrix}\right] * \exp\left(\frac{(\alpha + u)}{\omega\tau_2}\right) - \frac{E}{R_a} \quad (9)$$

The current at $x = \pi$, during the conduction interval is also equal to I_1, giving

$$I_1 = K_2\left[\cos\theta_2\sin\theta_2 - P\right] + \left\{\begin{matrix} K_2\left[\begin{matrix}\cos\theta_2\sin(\theta_2 - \alpha - u) + \\ P\end{matrix}\right] + \\ Iao\end{matrix}\right\} * \exp\left(\frac{-(\pi - \alpha - u)}{\omega\tau}\right) \quad (10)$$

Combining equations (9) and (10), gives a transcendental equation $f(u)$ which can be solved to obtain the commutation angle 'u' for the gating angle 'α'.

The free – wheeling diode D_2 in Fig. 3(c) becomes forward biased when the instantaneous supply voltage equals the source inductance. The induced voltage reverse biases D_2, until the angle after 'π' when this voltage is neutralized by the instantaneous supply voltage. The

current in the conducting thyristor begins to decay to zero and in an attempt to oppose this, the voltage in the armature circuit inductance forward biases 'D_2' to begin the freewheeling mode.

The reverse commutation of current from a conducting thyristor is opposed by the voltage induced in the source inductance. Defining 'ωt' from $x = \pi$, the current in a reverse commutating thyristor falls to zero from the value at $x = \pi + \beta$ i.e I_β.

So, in the interval $\pi + \beta < x < \pi + \beta + \lambda$, the conducting thyristor switches off and the expression for current during this interval is obtained from the describing equation of current from Fig.3 (d);

$$L_s \frac{di}{dt} + R_s i = -E_1 \sin(\omega t + \beta) \tag{11}$$

With the initial condition $i = I_\beta$, the current during the extinction process is;

$$i(t) = -K_1[\sin(\omega t + \beta - \theta_1)] - [K_1 \sin(\theta_1 - \beta) - I_\beta] * \exp\left(\frac{-t}{\tau_1}\right) \tag{12}$$

These equations for the current at the various intervals summed together, gives the current drawn from the supply by the motor load as shown in Fig. 2. Equation (12) was then simulated in a Matlab environment and the results displayed in Fig. 5 shows the a.c input power factor problem in graphics

Work is still been done to predict the harmonics and the relationships of the behaviour factors (power factor, harmonic factor, displacement factor, peak factor, distortion factor, etc).

2.12 Continuous Armature Current Mode

The waveform of currents of the drive when operating in a continuous armature current mode is as shown in Figure 4. The assumptions (Muhammed 1993 and Sen 1981)

- That the load is inductive
- That the load current is continuous.

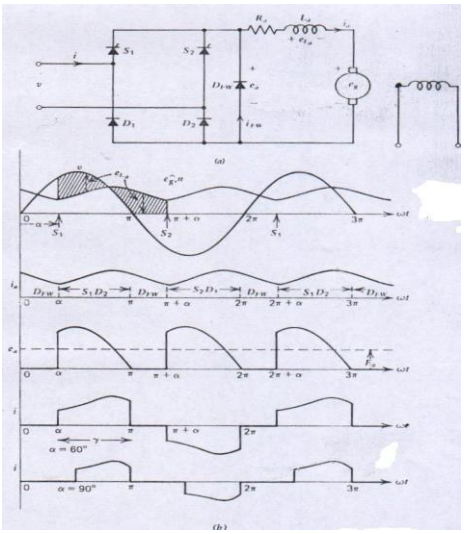


Figure 4: Speed control of a separately excited dc motor by a single phase Asymmetric bridge converter.

(a) Power circuit

(b) Voltage and current waveforms for continuous motor current

The instantaneous input current to an asymmetrical single – Phase Bridge can be expressed in Fourier series:

$$i_s(t) = I_{dc} + \sum_{n=1,2...}^{\infty}(a_n \cos n\omega t + b_n \sin n\omega t) \quad (13)$$

Where

$$I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} i_s(t)d(\omega t)$$

$$= \frac{1}{2\pi}\left[\int_{\alpha}^{\pi} i_a(t)d(\omega t) - \int_{\pi+\alpha}^{2\pi} i_a(t)d(\omega t)\right]$$

Simplifying yields,

$$I_{dc} = 0 \quad (14)$$

$$a_n = \frac{1}{\pi}\int_{\alpha}^{2\pi} i_s(t)\cos n\omega t d(\omega t) = \frac{1}{\pi}\left[\int_{\alpha}^{\pi} I_a(t)\cos n\omega t d(\omega t) - \int_{\pi+\alpha}^{2\pi} I_a(t)\cos n\omega t d(\omega t)\right]$$

$$= \frac{-2I_a}{n\pi}\sin n\alpha \quad \text{For} \quad n = 1,3,5.... \text{ Odd}$$

Also,

$$b_n = \frac{1}{\pi}\int_{\alpha}^{2\pi} i_s(t)\sin n\omega t d(\omega t) \quad (15)$$

$$= \frac{2I_a}{n\pi}(1+\cos n\alpha) \quad \text{for n = 1,3,5...} \quad (16)$$

Equation (13) can be written as

$$i_s(t) = \sum_{n=1,3,5...}^{\infty}\sqrt{2}I_{sn}Sinn(n\omega t + \phi_n) \quad (17)$$

where, $I_{sn} = \frac{1}{\sqrt{2}}\left(a_n^2 + b_n^2\right)^{\frac{1}{2}}$ (18)

This is the nth harmonic current of the input.

Substituting for a_n and $b_n = \frac{2\sqrt{2}I_a}{n\pi}Cos\frac{n\alpha}{2}$ (19)

And, $\phi_n = \frac{-n\alpha}{2}$ (20)

Hence equation (17) becomes;

$$i_s(t) = \frac{4I_a}{n\pi}\sum_{n=1,3,5....}^{\infty}\left[\cos\frac{n\alpha}{2}\sin\left(n\omega t - \frac{n\alpha}{2}\right)\right] \quad (21)$$

The fundamental current is obtained by setting n = 1

From equation (19),

$$I_{s_1} = \frac{2\sqrt{2}}{\pi}I_a\cos\frac{\alpha}{2} \quad \text{(i.e. n = 1)} \quad (22)$$

Determination of I_s :

$$I_s = \left[\frac{2}{2\pi}\int_{\alpha}^{\pi} I_a^2 d(\omega t)\right]^{\frac{1}{2}}$$

$$= \left[\frac{I_a{}^2}{\pi}|\omega t|\right]_{\alpha}^{\pi}$$

$$= I_a\left[1-\frac{\alpha}{\pi}\right]^{\frac{1}{2}} \quad (23)$$

Power factor (Muhanned 1993) is defined as;

$$\text{PF} = \frac{I_{s_1}}{I_s}\cos\phi_{s_1}$$

Where,

$\phi_{s_1} = -\frac{\alpha}{2}$ From equation (20)

and,

$$\text{PF} = \frac{I_{s_1}}{I_s}\cos\frac{\alpha}{2} = \left[\frac{\frac{2\sqrt{2}}{\pi}I_a\cos\frac{\alpha}{2}}{I_a\left(1-\frac{\alpha}{\pi}\right)^{\frac{1}{2}}}\right]\cos\frac{\alpha}{2}$$

$$= \frac{\sqrt{2}\left[1+\cos\alpha\right]}{\left[\pi(\pi-\alpha)\right]^{\frac{1}{2}}} \quad (24)$$

Equation (24) shows the relationship between Power Factor and the thyristor firing angle. An increase in the firing angle reduces the power factor

The expression for harmonic factor (Muhammed 1993) is;

$$\text{HF} = \left[\frac{I_{s_1}^2 - I_{s_1}^2}{I_{s_1}^2}\right]^{\frac{1}{2}} = \left[\left(\frac{I_s}{I_{s_1}}\right)^2 - 1\right]^{\frac{1}{2}}$$

Substituting for I_s and I_{s_1}

$$\text{HF} = \left[\frac{\pi(\pi-\alpha)}{4(1+\cos\alpha)} - 1\right]^{\frac{1}{2}} \quad (25)$$

If ϕ_{s_1} is the angle between the fundamental component of the input current and AC input voltage, then the displacement factor DF is:

$$\text{DF} = \cos\phi_{s_n} = Cos\frac{-n\alpha}{2}$$

$$Cos\phi_{s_1} = \cos\left(\frac{-\alpha}{2}\right) \quad (26)$$

3.0 RESULTS AND DISCUSSION

The expressions derived in equation (12) and (21) for the instantaneous input current are plotted in Figures 5 and 6 for a firing angle of the thyristors of the drive. It shows the non – sinusoidal waveform of the ac input current which is due to the presence of harmonics in the supply current. Work is still being done to predict the level of harmonics when the motor is operating in the discontinuous armature current mode. However, the corresponding harmonics are displayed in Figure 7 when operated in the continuous mode and their behaviour factors presented in Figure 8. Evidently, the PF, HF and the DF vary with the delay or firing angle.

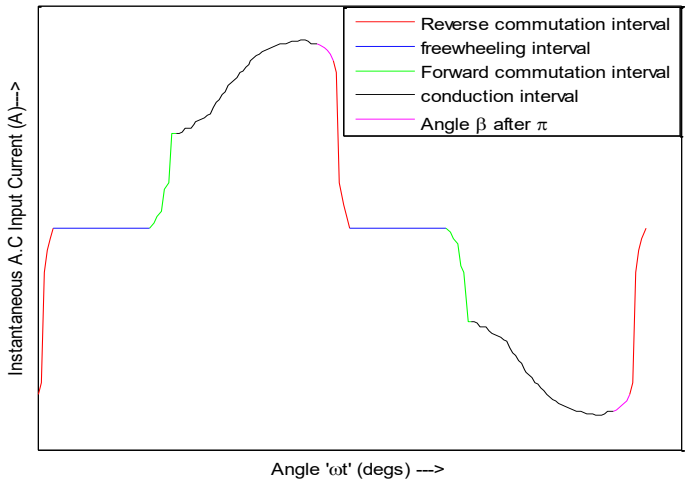


Figure 5: Motor input current for a '$60^{0'}$ Firing angle

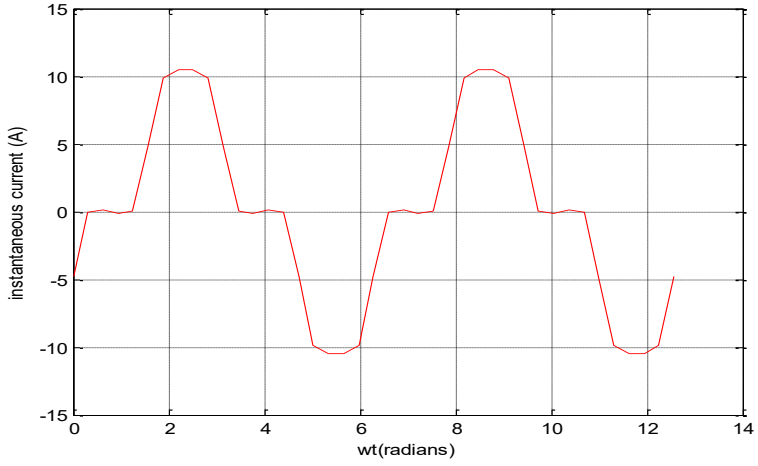


Figure 6: Waveform of input current for a delay angle of 'α' = 60 degrees

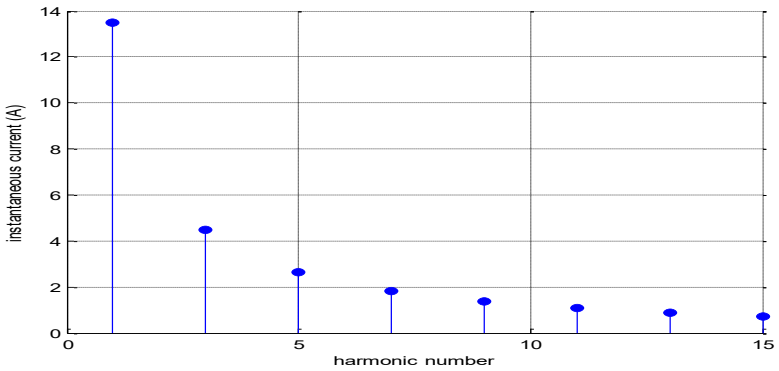
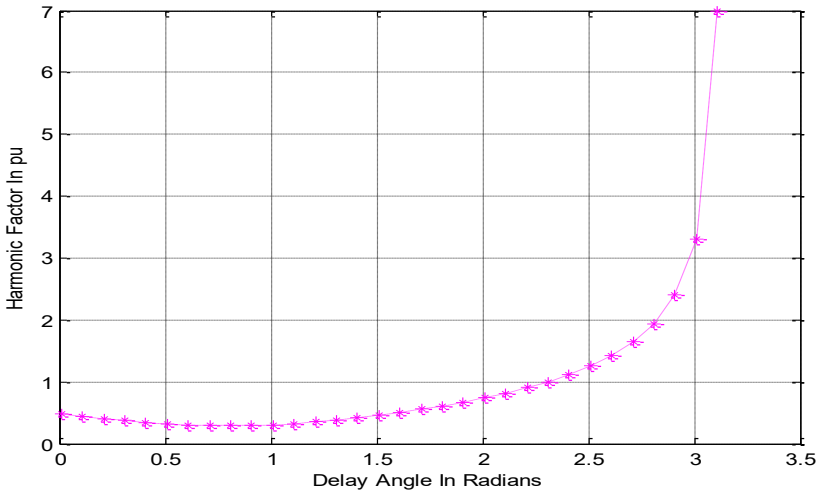
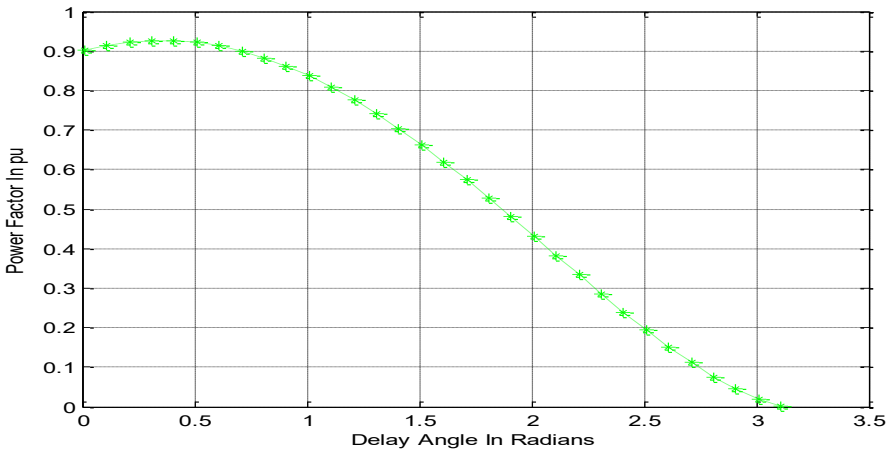


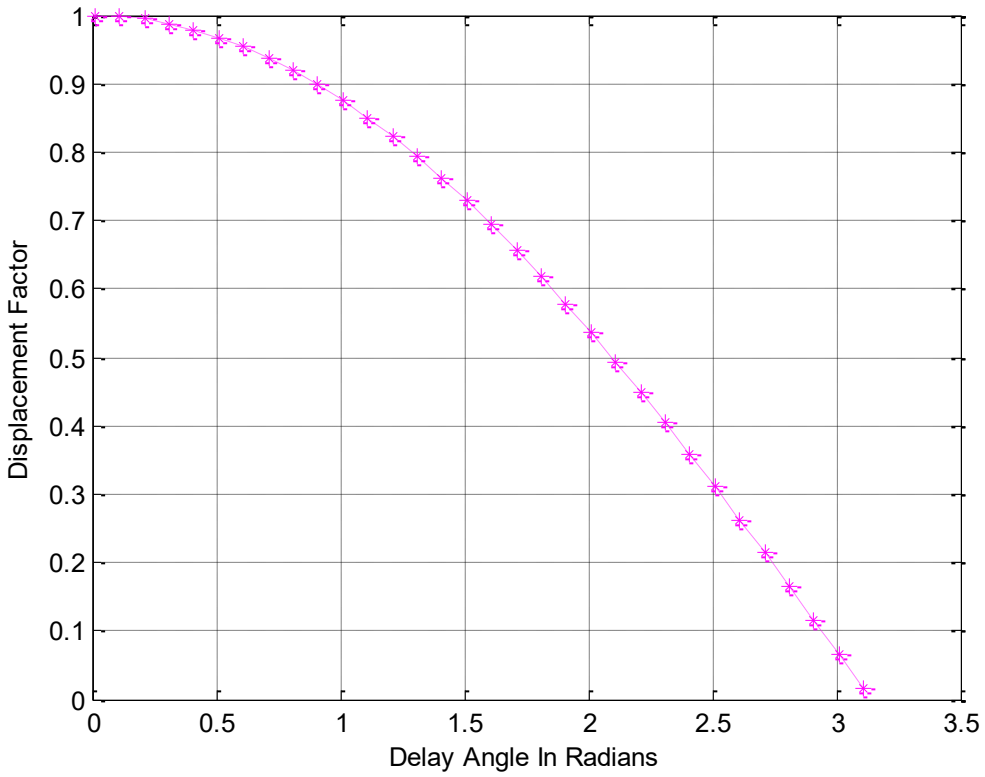
Figure 7: Harmonics of the single – phase asymmetric bridge converter



(a)



(b)



(C)

Figure 8: Behaviour factors of the bridge
(a) Harmonic factor
(b) Power factor
(c) Displacement factor

It should be noted that the power factor worsen as the number of such drives connected to the supply system increase The theory for this situation is being developed.

4. CONCLUSION

The realization of the full potential of steel plants already built in the country would increase the level of non – linear loads connected to the National Grid. Unless there is an understanding of the effects of these loads and adequate implementation of harmonic suppression and reduction techniques, more problems are bound to arise. This paper has contributed to locally available information on harmonic sources and their effect on the supply line. Increased local interests in the phenomenon of equipment and system failure as a result of harmonic induced resonances are hereby encouraged. An important point to note is that the power factor of the supply system worsens as the firing or delay angle of the thyristors of the drive increases.

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