PERFORMANCE ANALYSIS OF THYRISTOR-SWITCHED CAPACITOR (TSC) STATIC VAR COMPENSATOR (SVC)

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ABSTRACT

In an electric utility network, it is desirable to regulate the voltage within a narrow range of its nominal value (±5% range around their nominal values). Since the load varies from time to time, the reactive power balance in a grid varies as well. It can be shown that the voltage drop on the line is a function of the reactive power flowing on the line. To control dynamic voltage swings under various system conditions and thereby improve the power system transmission and distribution performance, a fast acting Static VAr Compensator (SVC) is required to produce or absorb reactive power so as to provide the necessary reactive power balance for the system. The function of the SVC is to maintain the voltage of the bus connected at a constant value. In this paper an SVC configuration known as Thyristor-Switched Capacitor (TSC) is examined, as applied to shunt reactive compensation. The compensator was connected to the load end of a system operating at 0.7 power factor. By supplying some value of reactive power, it raised the power factor to an optimal value of 0.96, thereby improving the efficiency of the system.

***Keywords**: Reactive power, var compensator, voltage regulation, TSC, transmission*

1. Introduction

Most loads, including transformers, reactors, ac machines, transmission lines (series inductive reactance), etc. are inductive. So, for proper operation, they require reactive power which must be supplied from the source. This reactive power gives rise to reactive current which increases the current flowing on the lines, leading to higher power losses. The lagging reactive power drawn by the inductive loads makes electric power system voltage to sag. Thus, voltage drop on electric utility network depends on the flow of reactive power (Weedy, 1987). In Electrical Power System, Static VAr Compensators (SVCs) are used to control the flow of reactive power. Static VAr compensators have thus been used for years by utilities to control reactive power flow in transmission and distribution systems and consequently, help to stabilize weak systems, minimize line (I^2R) losses, increase power transfer capability, enhance transient and steady-state stability, balance three-phase loads, damp oscillations, reduce voltage flicker and provide greater dynamic voltage regulation (Jen-Hung *et al*, 1999; Mustapha and Azeddine, 2006; Xuechun *et al*, 2001; Parniani and Iravani, 1998). Any modest reduction in transmission losses, by limiting the flow of load reactive current along the transmission lines, means considerable cost savings in both power capacity and energy production (IEEE, 1994).

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The TSC is connected in parallel with and near the load. It provides dynamic var compensation, and uses combinations of variable inductive and capacitive elements with solid-state devices, for switching to achieve faster response to changes in system conditions. There must be sensing and control system to decide how much reactive power must be applied to the system to achieve the required level of compensation (Bill and Gerald, 2000). The control system determines the gating instants and issues the gating pulses to the solid-state switches in response to some system changes.

2. Materials and Methods

2.1 Modelling of Thyristor-Switched Capacitor (TSC)

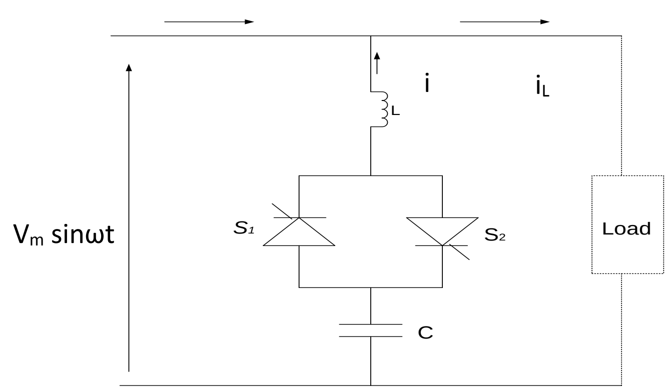

Figure 1: Thyristor-switched capacitor (TSC)

The TSC Configuration-Fig. 1 (Frank and Ivner, 1981) consists of a number of different sized shunt capacitor banks which are switched on and off by a pair of anti-parallel thyristors. Since the bank size is arranged with a progression of 1, 2, 4, 8, etc. any rating of capacitance from zero up to the total of the ratings can be switched in or out with a graduation of one unit. By suppressing thyristor gate pulses the reactive power through the capacitor ceases abruptly when the capacitor current reaches a natural zero current which also corresponds to the capacitor voltage equal to the maximum ac system voltage. Since the currents are switched at zero crossing points, the harmonic generation is very low (Frank and Landstrom, 1971). However, when the thyristor is non-conducting, the dc voltage on the capacitor plus the ac system voltage will cause voltage stresses of twice the system voltage across the thyristor. A series damping inductor is used to limit the rate of rise of current through the thyristors and to prevent resonance with the system network. A major property of this configuration is stepwise control. The final information is the number of capacitor banks to be connected to the ac system. Thus, the control must be rigidly synchronized to the ac system voltages, otherwise misfiring could occur. Three single-phase branches may be connected in star or delta to form a three-phase bank. as shown in Figure 2.

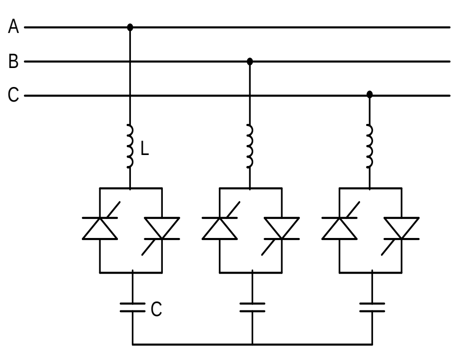

Figure 2: 3-phase bank

The inductor is a minor component in the TSC. Its function is to limit the rate of rise of current through the thyristors and to prevent resonance with the network. The value of the inductive reactance, X_L is normally 6 % of the capacitive reactance, X_C (Juan *et al*). Transient free conditions are maintained by switching the capacitor

$$A = V_{co} - \frac{V_m}{1-\omega^2 LC}\sin\alpha$$

in and out at $\frac{dV}{dt} = 0$. (Scott and Powsiri, 2002; Scott and *et al*, 2002). That is the capacitor is only switched at the peak of the applied voltage. In other words, prior to switching in, the voltage across the capacitor, $V_{co} = V_{s,\,peak}$

From Fig. 1:

$$L\frac{di_c}{dt} + v_c = V_m \sin\omega t \tag{1}$$

Where , i_c is the current through the compensator and v_c is the voltage across the capacitor.

$$i_c = C\frac{dv_c}{dt} \tag{2}$$

$$LC\frac{d^2 v_c}{dt^2} + v_c = V_m \sin\omega t$$

(3)

$$\frac{d^2 v_c}{dt^2} + \frac{1}{LC}v_c = \frac{V_m}{LC}\sin\omega t \tag{4}$$

The solution of equation (4) can be found to be:

$$v_c = A\cos\omega_r t + B\sin\omega_r t + \frac{V_m}{1-\omega^2 LC}\sin\omega t$$

(5)

From equation (2)

$$i_c = -\omega_r C A\sin\omega_r t + \omega_r CB\cos\omega_r t + \frac{\omega C V_m}{1-\omega^2 LC}\cos\omega t$$

(6)

$$B = -\frac{\omega V_m}{\omega_r\left(1-\omega^2 LC\right)}\cos\alpha$$

$\omega_r = \sqrt{\frac{1}{LC}}$ is the system

At switch-on, t = 0, ωt = α (thyristor firing angle),

$v_c = V_{co}$,

Thus equation (6) becomes:

$$i_c = \frac{\omega C V_m}{1-\omega^2 LC}\cos(\omega t + a) - \frac{\omega C V_m}{1-\omega^2 LC}\cos\alpha\cos\omega_r t + \omega_r C\left(\frac{V_m \sin\alpha}{1-\omega^2 LC} - V_{co}\right)\sin\omega_r t \quad (7)$$

Equation (7) can also be expressed as:

$$i_c = \frac{V_m}{X_c - X_L}\cos(\omega t + a) - \frac{V_m}{(X_c - X_L)}\cos\alpha\cos\omega_r t + \frac{1}{\omega_r L}\left(\frac{X_c V_m \sin\alpha}{(X_c - X_L)} - V_{co}\right)\sin\omega_r t \quad (8)$$

Where, X_c and X_L are the compensator capacitive and inductive reactance respectively, Vm is the maximum value of the system voltage. Equation (8) is the current that flows through the compensator at a given time, t. The capacitor is switched in and out at the instant of current zero crossing, which also corresponds to the source voltage peak value, V_m, and the capacitor voltage V_{co} is equal to V_m. Thus the TSC employs integral half-cycle control where the capacitor is either fully in or out of the circuit. In other words, the average switching delay angle is one half of a cycle Juan *et al*).

So i_c can be expressed in Fourier series as:

$$i_c = \frac{a_0}{2} + \sum_{n=1,2}^{\infty}\left(a_n \cos n\omega t + b_n \sin n\omega t\right) \quad (9)$$

Where:

$$a_0 = \frac{1}{\pi}\int_{\alpha}^{3\pi/2}\left(x_1\cos\omega t - x_1\cos\alpha\cos\omega_r t + x_2\sin\alpha\sin\omega_r t - x_3\sin\omega_r t\right)$$

$$a_n = \frac{1}{\pi}\int_{\alpha}^{3\pi/2}\begin{pmatrix} x_1\cos\omega t\cos n\omega t - x_1\cos\alpha\cos\omega_r t\cos n\omega t + \\ x_2\sin\alpha\sin\omega_r t\cos n\omega t - x_3\sin\omega_r t\cos n\omega t\end{pmatrix}d\omega t$$

$$b_n = \frac{1}{\pi}\int_{\alpha}^{3\pi/2}\begin{pmatrix} x_1\cos\omega t\sin n\omega t - x_1\cos\alpha\cos\omega_r t\sin n\omega t + \\ x_2\sin\alpha\sin\omega_r t\sin n\omega t - x_3\sin\omega_r t\sin n\omega t\end{pmatrix}d\omega t$$

$$x_1 = \frac{V_m}{X_c - X_L}$$

$$x_2 = \frac{1}{\omega_r L}\left(\frac{X_c V_m}{(X_c - X_L)}\right); \quad x_3 = \frac{V_{co}}{\omega_r L}$$

3. RESULTS AND DISCUSSION

3.1 Analysis

Let us consider the following system: A single-phase motor operates off a 400V, 50Hz supply, developing 10-kW power with an efficiency of 84 percent and power factor (p.f.) of 0.7 lagging.

So, the input volt-ampere to the motor is

$$IV = \frac{10 \times 1000}{0.84 \times 0.7} = 17000VA$$

Current taken by motor, I = $\frac{17000}{400} = 42.5A$

Active component of current,

I_a = 42.5 x 0.7 = 29.75A

$$\theta = \cos^{-1}(0.7) = 45.573^o$$

Reactive component of current,

I_{r1} = 42.5 x sin (45.573°) = 30.35A

Reactive power = 400 x 30.35 = 12140VAr.

In order to raise the system power factor from 0.7 to 0.9, the following calculations cab be used:

Active component of current, I_a = I x 0.9 = 29.75A

Apparent current $I = \frac{29.75}{0.9} = 33.06A$

Reactive component of current,

$I_{r2} = 33.06\,x\,\sin\left(\cos^{-1}(0.9)\right) = 14.41A$

Capacitor current required for compensation,

I_c = 30.35 – 14.41=15.94A

$$C = \frac{15.94}{2\pi\,x\,50\,x\,400} = 127\,\mu F$$

$$X_c = \frac{10^6}{2\pi\,x\,50\,x\,127} = 25.\Omega$$

Reactive power = $Q_c = \frac{V^2}{X_c} = 6384.7\,VAr$

$$X_L = 0.06\,x\,X_c = 1.5\Omega$$

The system voltage (v_s), load current (i_L) and load reactive power (q_L) before compensation are shown in Fig. 2

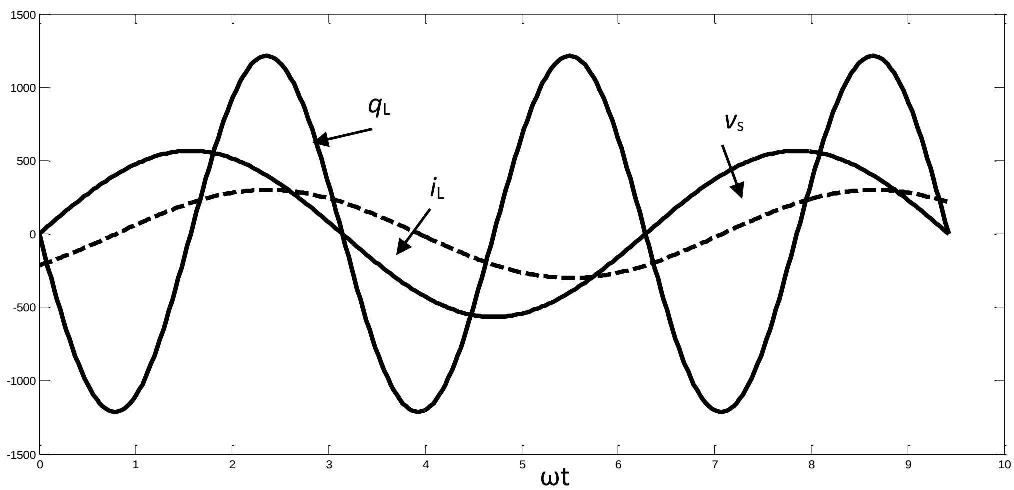

Figure 2: Waveforms of system voltage, v_s and load current, i_L at power factor = 0.7 lagging

Now, to improve the power factor, a TSC can be installed and switched on at the peak of the system voltage (i.e, when α = 90°). Figure 3 shows the current supplied by the compensator.

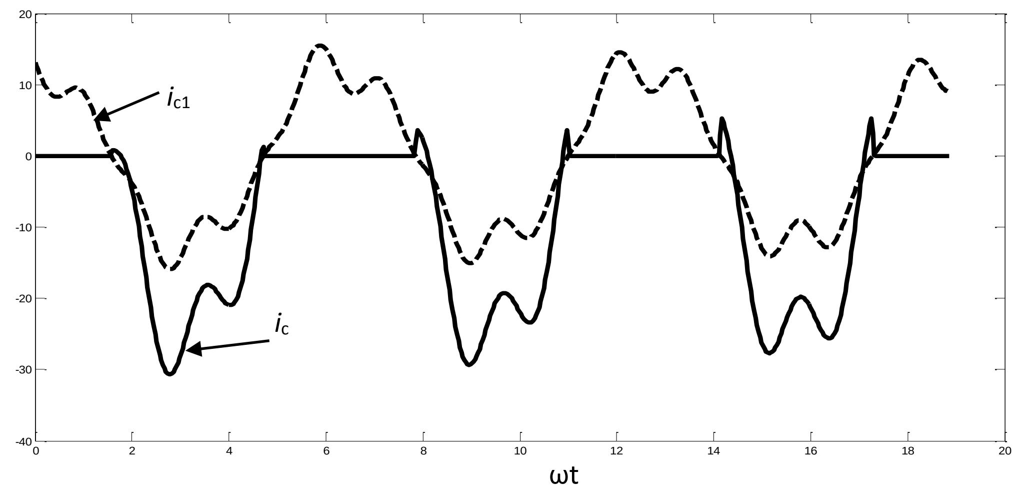

Figure 3: Compensator current

i_c (ωt) – Compensator current

i_{c1} (ωt)– Fundamental component

This plot was generated from equation (9), with the parameters as stated above.

Figure 4 shows how the application of TSC has raised the system power factor from 0.7 to 0.9 lagging. The current flowing from the source has become $i_s = i_L - i_c$, lagging the system voltage v_s by 25.84° to obtain 0.9 power factor, the TSC supplied 6385VAr, see above.

Figures 5 and 6 show the achievement of optimum power factor of 0.96. In this case, the TSC generates 8672VAr., calculated as before.

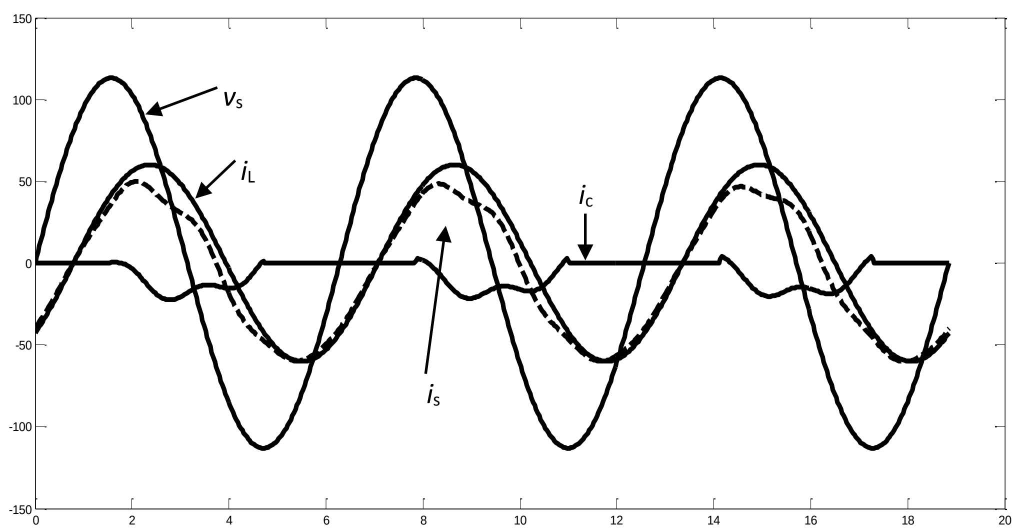

Figure 4: Power factor improvement (0.7 to 0.9 lagging) by the use of TSC

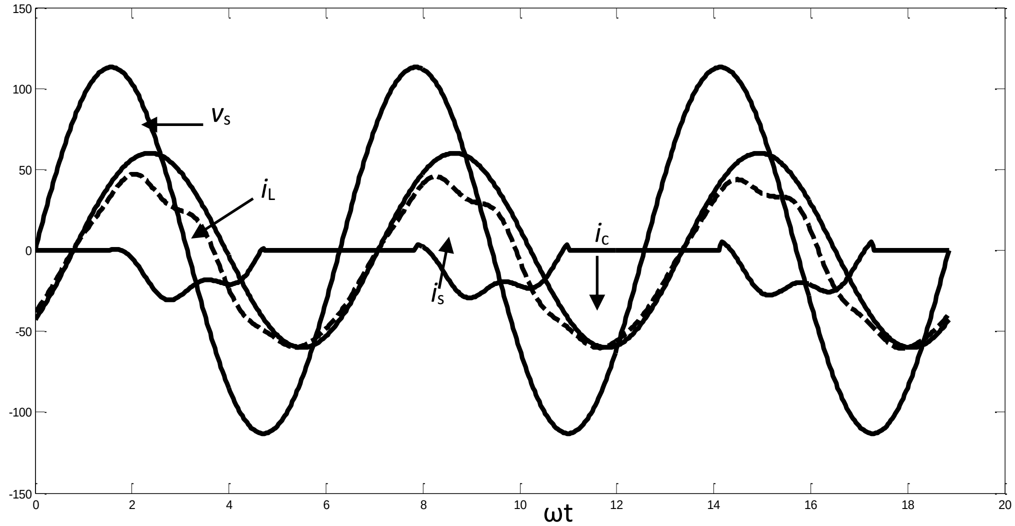

Figure 5: Power factor was raised to 0.96 by the use of TSC

Figure 5 shows the ac system voltage v_s leading the load current i_L by 45.57° before installation of TSC. After the installation of TSC, the new current drawn by the load is shown to be i_s. It can be seen that v_s now leads i_s by 16.26°.

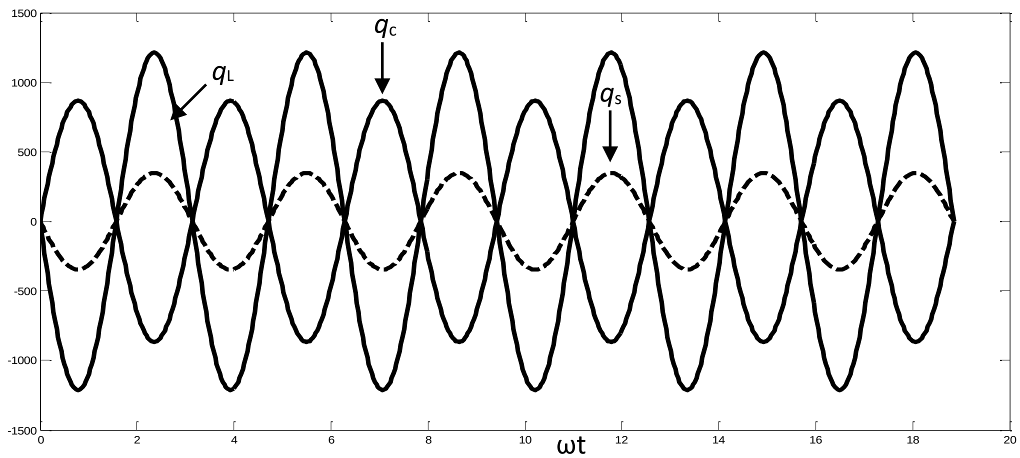

Figure 6: Waveforms of reactive power absorbed by load (q_L) and supplied by TSC (q_c) to achieve 0.96 power factor

q_L(ωt) – reactive power drawn by load

q_c (ωt) – reactive power supplied by TSC

q_s (ωt) – reactive power from source

It can be observed from Fig. 6 that the reactive power drawn by the load before the installation of TSC is q_L. After installation of TSC the reactive power taken from source by the load has dropped to q_s. q_c is the reactive power generated by the TSC - required for compensation.

3.2 Derivation of Economical Power Factor:

Economical power factor is the power factor at which the gain or savings obtained from installing capacitor banks for power loss reduction in a distribution system is equal to or greater than the cost of the capacitor banks and their cost of installation in the system (Symonds, 1980). It is also the power factor at which the net saving is maximum.

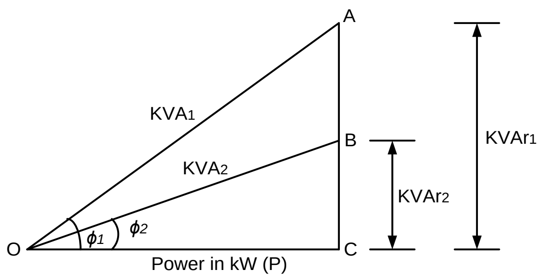

Figure 7: Power triangle for Economical power factor and net savings

Suppose a consumer is charged at $A per KVA maximum demand plus a flat rate per KWh. Further, suppose he is taking power of P [kW] at a power factor of cos ϕ_1. Suppose by installing capacitors he improves his power factor to cos ϕ_2 (his power consumption P remaining the same), reduction in his KVA maximum demand is, from Fig.7.

$$KVA_1 - KVA_2 \quad = \quad \left(\frac{P}{\cos\phi_1} - \frac{P}{\cos\phi_2} \right) \qquad (10)$$

Since charge is $A per KVA maximum demand, his annual saving on his account is:

$$\$\, A\left(\frac{P}{\cos\phi_1} - \frac{P}{\cos\phi_2} \right) \qquad (11)$$

The KVAr difference: $\left(KVAr_1 - KVAr_2\right) \quad = \quad \left(P\tan\phi_1 - P\tan\phi_2\right)$ is neutralized by the leading KVAr supplied by the capacitors. The cost of power factor improvement equipment is taken into account by way of interest on capital required to install it plus depreciation and maintenance expenses. Thus, the greater the KVAR reduction, the more costly the P.F improvement capacitor and hence greater the charge on interest on capital outlay and depreciation.

A point is reached when any further improvement in power factor will cost more than savings in the bill. Hence it is necessary for the consumer to find out the value of power factor at which his net savings will be maximum. This value can be found if (i) annual charge per KVA maximum demand and (ii) the cost per KVAr rating of capacitor are known. If the cost per annum in interest and depreciation on the capacitor installation is $C per kVAr, then

$$\text{Cost per annum=}\quad \$\text{C}\left(P\tan\phi_1 - P\tan\phi_2\right) \qquad (12)$$

Net annual saving is:

$$S= \left[AP\left(\frac{1}{\cos\phi_1} - \frac{1}{\cos\phi_2} \right) - CP\left(\tan\phi_1 - \tan\phi_2\right) \right] \qquad (13)$$

Figure 8 shows the plot of power factor (cos ϕ_2) versus net saving S in $.

It can be observed in Fig. 8 that the net saving has maximum value ($ 45,660.00) at power factor of 0.96. This then is the optimum power factor, beyond which the power factor improvement is no longer economical.

4. CONCLUSION

The equations governing the performance of the TSC were derived and then used to illustrate how the reactive power drawn from the ac supply, by an inductive load, can be compensated for. The 0.7 power factor lagging could be raised to the optimum value as shown in Figs. 4, 5 and 6 – and consequently attaining an overall improvement in the performance of the ac system. Fig. 8 shows that the optimal power factor is 0.96.

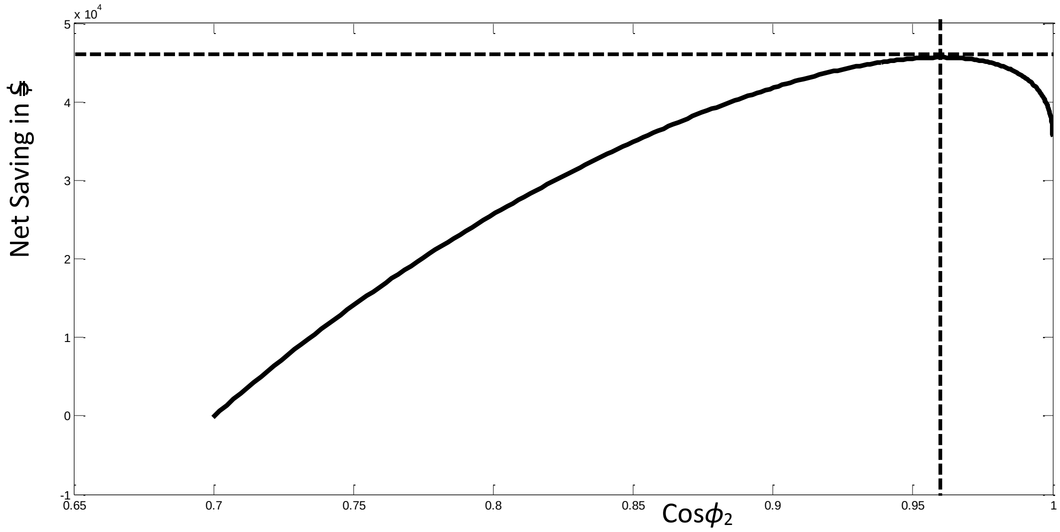

Figure 8: Power factor versus Net Saving in naira.

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