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# Reactive Power Compensation using STATCOM Based on Instantaneous Reactive Power Theory

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## *Abstract*

Reactive power can have a range of negative impacts on energy generation and consumption in a power system network. These include creating unnecessary increases in generation, leading to the overall decline in grid efficiency and a drastic waste of resources. Reactive power compensation is, therefore, critical for improved system performance and elevated productivity. This research aims to design and simulate a three-phase reactive power compensation model using a Static Synchronous Compensator (STATCOM) that can improve the system's power factor and can also provide effective suppression of the system harmonics. This will be implemented using MATLAB/Simulink software in which the STATCOM will be connected to a 3-phase load system fed from 5kVA, 11kV/400V source. Based on an Instantaneous Reactive power (IRP) theory, the load reactive power is harnessed to generate an inverted signal which will drive the gates of semiconductor devices of the STATCOM inverter to cancel out the reactive current consumed by the load. Initially, a purely resistive load is connected to the system where the model response is observed through the Simulink display blocks. Subsequently, an incremental amount of reactive load

is added in three steps: 4126 Var, 8576 Var and 13470 Var respectively. In each case, the response of the model is observed and analyzed. Conclusively, the designed model can instantly generate a compensating power with an ideal unit power factor in each case. Using a Fast Fourier Transform (FFT) signal analyzer, the outcome of the harmonic distortion imposed by the load currents has also been eliminated.

**Keywords:** Reactive Power Compensation, STATCOM, Instantaneous, Reactive Power Theory, Energy Generation

# *Introduction*

**Background of The Study**

Energy demand has, in recent years, exhibited a geometrical growth whereas the supply is not meeting up due to several challenges, especially in underdeveloped worlds [1][2]. This can be observed in the power sector where system networks are repeatedly losing stability due to energy imbalance as a result of reactive power issues. Reactive power is, indeed, taking a new incremental dimension in recent years as a result of two factors: an increased penetration of variable renewable energy sources such as solar/wind and an expanding demand for power electronics due to technological advancements[3][4]. When the voltage and current are out of phase, a large amount of energy will be wasted resulting to an inefficient use of power. While reactive power Cannot be completely eliminated, there is a need to maintain an equilibrium between reactive production and consumption through effective reactive power compensation. Efficient reactive power production and management is, therefore, essential in the power system network. To demonstrate the benefit of reactive power compensation, Fig. 1 illustrates two sets of a simple power system where an induction motor is fed from a utility. In Fig. 1 (a), the reactive power requirement of the load is taken directly from the utility which forces it to deliver the undesired 100% or more of its rated capacity. In Fig. 1 (b) on the other hand, the utility is relieved of the stress of generating the reactive power

requirement of the load by connecting a compensator near the load center.

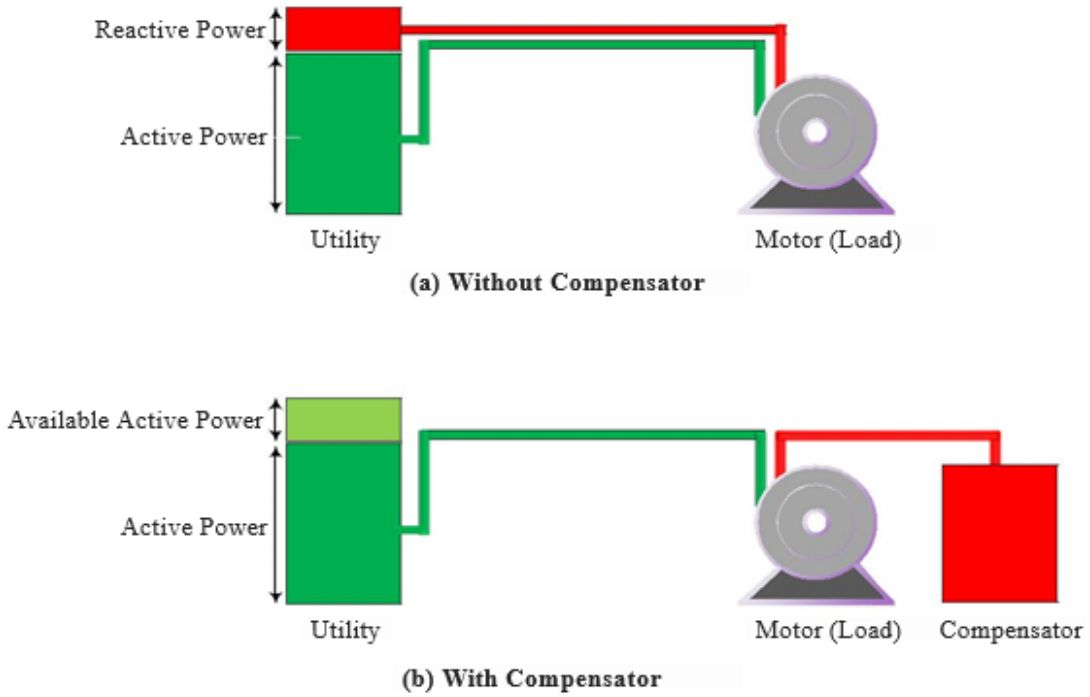



*Figure 1:* ***The benefit of reactive power compensation in a power system network***

**Statement of the Problem**

In today's power system network where the loads are dominantly inductive, reactive power control becomes necessary. The reactive power present in a system is usually determined from the system's power factor which is an indicator of how efficiently the electrical energy is converted into useful work. In any system where reactive power is effectively compensated, this factor ranges from above 0.85 to an ideal value of 1.0. A factor of 0.85 and below indicates that the system is heavily loaded with reactive power. In this condition, the generation is likely to get overloaded which may lead to a consequent malfunction and or breakdown. A poor power factor due to the system's reactive power is a result of considerable and unnecessary energy consumption, leading to a reduction in the generation capacity. Even though reactive power is important in energy life cycle, its existence becomes a burden since there are existing solutions that can be implemented easily and

inexpensively. In addition, such increased energy consumption adds to the total running cost of equipment and installations. A STATCOM with an effective control technique will offer the following benefits when implemented in a power system:

a. Excellent grid power factor which will drastically minimize energy consumption losses.
b. Improved voltage quality which in turn provides stability in the system's equipment operation.
c. 20 – 30% reduction in the system's power loss.
d. Reduced equipment size and capacity for the same purpose.
e. Extended equipment service life.
f. Reduced running and consumption costs of electrical energy.
g. Safest and reliable compensation technology.

**Objectives of the Study**

1. To design a STATCOM that will generate and inject the amount of reactive power consumed by a 3-phase load and which will improve the load power factor to unity.
2. To suppress the system's total harmonic distortion below 1%.

## LITERATURE REVIEW

Various approaches to compensating system reactive power have been presented in different literature.

The most common and popular methods include the use of synchronous generators and passive devices such as capacitor banks and shunt reactors. When capacitors are used to compensate for reactive power, several units are combined to form a bank connected in a delta or star arrangement. The resulting unit is protected in an enclosure made of non-corrosive metal such as aluminum. The enclosure contains all the necessary auxiliary facilities such as busbars, insulators, etc. Depending on the size of the bank, this can be placed at the load end or the point of common coupling [5][6][7].

An improved capacitor performance with better compensation efficiency can be achieved through various techniques such presented in [8]. In a similar study,

[9] established an enhanced method called Dolphin Optimization Algorithm (DOA) which involves a proper selection of sizes and locations of capacitor banks. Using two case studies—the IEEE 16-bus and the 33-bus, they assessed various load models and obtained the best reactive power compensation. [10] have also conducted similar research to optimize the reactive power compensation with fixed-step capacitor banks using the black hole optimization (BOH) technique. A new approach to improving the power factor of both leading and lagging loads that employ PIC Microcontroller has been implemented by [11]. A major requirement in the implementation of this method is figuring out the zero crossing of voltage and current signals. The capacitive and inductive banks are then used to compensate for the reactive power according to the reactive load type. This, however, presents a bit of an issue since it cannot vary with the variation of the system's reactive power. To remedy this, [12] and [13] have come up with an automatic power factor correction (APFC) system of capacitor banks that dynamically monitors and establishes a required level of the system's power factor. The APFC makes use of Microcontroller programmed to track the load power factor around a predetermined level. In some applications, the performance of the reactive capacitors is also facilitated through the use of modern information and communication technology (ICT) gadgets. This accelerates the remote control and reconfigurations of the capacitor banks[14].

Synchronous Generators are also popular in reactive power compensation applications. Depending on the excitation of the filed winding, they can be configured to either supply or absorb reactive power. When the field is under-excited, the synchronous Generator absorbs reactive power and when over-excited, it supplies reactive power. The generators have an advantage (over capacitor banks) of supplying a relatively more accurate required amount of reactive power with much fewer auxiliary devices. Researches are conducted virtually and new implementation strategies are being put in different positions in the power system network[15] [16].

These conventional methods of reactive power compensation are still stuck to, even with the advent of flexible AC transmission system (FACTS) devices[17][18]. However, some avoidable shortfalls have been observed from these methods. For example, capacitors are generally associated with high

reactive impedance which can lead to energy loss in the system. Besides, the use of switch capacitors is limited to their ratings, (frequent overrating leads to short life due to dielectric discharge). Capacitors are prone to injecting harmonics in addition to the load system harmonics which can seriously downgrade the power system quality. The reactive power output of synchronous generators or condensers is restricted by heating of armature winding or field current which constitutes a considerable error in reactive power generation.

To overcome these challenges, this research presents a better option using one of the contemporary Flexible alternating current transmission systems (FACTS) devices, the STATCOM. This power electronics device has offered a list advantage over conventional methods: Faster response to transient and other power disturbances, effective harmonic suppression, minimized size, lower cost, and wider operating range.

## MATERIALS AND METHOD

To realize the results, a three-phase generation rated 11kV/400V, 50Hz feeding a system of inductive loads with a level of reactive power consumption is modeled using MATLAB/Simulink software. The same software is used to model the static synchronous compensator (STATCOM) connected across the supply-load lines at the point of common coupling (PCC). The complete scheme is illustrated in Fig. 2.

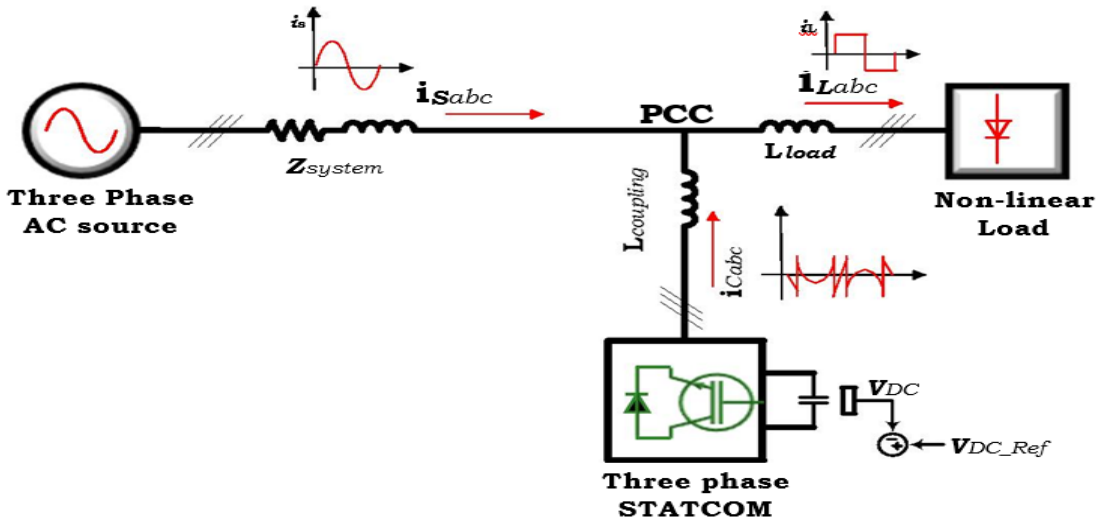



*Figure 2:* ***Schematic diagram of a 3-phase STATCOM connected at PCC***

As seen in the figure, the STATCOM is set in a closed-loop control to dynamically regulate the system's power factor by injecting or absorbing reactive power for a maintained, balanced supply-load relationship. This is based on an instantaneous reactive power theory (IRPT) which allows for the calculation of both active (p) and reactive power (q) at any given moment in time. The block diagram in Fig. 3 illustrates the sequence involved in this operation.

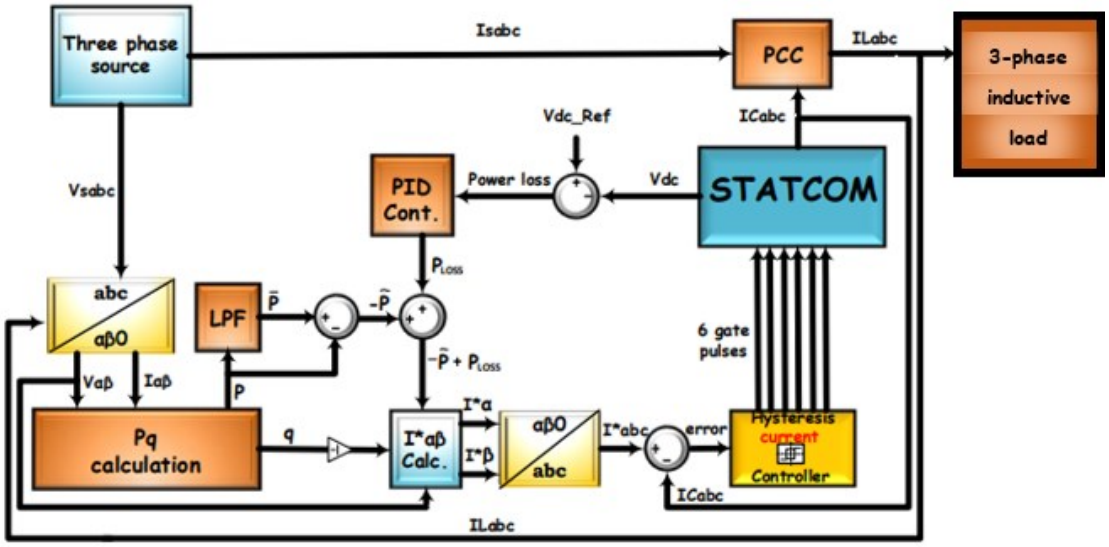



*Figure 3:* ***block diagram of the STATCOM illustrating operational sequence***

The first step in the operational phases of the diagram is the conversion of the 3-phase inductive load currents $\boldsymbol{I_{Labc}}$ and the source voltage $\boldsymbol{V_{Sabc}}$ to a 2-phase orthogonal ($\alpha\beta 0$) fixed reference frame. This is to simplify mathematical calculations and to facilitate the control of the STATCOM inverter. This is shown in the *abc*-to- $\alpha\beta 0$ block. The 2-phase frame is used to extract the system's instantaneous active and reactive power (pq) used for generating the reference currents ($I_{\alpha}^{*}$ and $I_{\beta}^{*}$) after passing through a low passive filter (LPF). This 2-phase frame reference current is then passed through a conversion block to restore the original 3-phase quantities, $\boldsymbol{I_{abc}^{*}}$. This is known as inverse Clark's transformation or $\alpha\beta 0$ -to- *abc.* This reference current is controlled using the hysteresis loop control technique and is used for firing the gate signals of the STATCOM inverter to compensate for the system's reactive currents. The major blocks involved in the

STATCOM control operation are explained to some detailed as follows:

**abc-to- $\alpha\beta$0 block: Clark's Transformation:**

The orthogonal components of the system in stationary reference frame are obtained using the following transformation matrices:

$$\begin{bmatrix} V_o \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} I_o \\ I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (2)$$

Where a, b & c represent the 3-phase input signals and the $\alpha$ & $\beta$ represent the two orthogonal components; $\sqrt{\frac{2}{3}}$ is a transformation coefficient.

**pq block: determination of active (p) and reactive power (q).**

In a balance 3-phase system, the zero sequence components, $V_o$ and $I_o$ become zero. Therefore, the instantanous p and q are given by:

$$\begin{aligned} p &= V_\alpha I_\alpha + V_\beta I_\beta \\ q &= V_\beta I_\alpha + V_\alpha I_\beta \end{aligned} \quad (3)$$

This can be represented in matrix form as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (4)$$

Now for the fact that the $\alpha$ and $\beta$ components of current are non-sinusoidal due to inductive load, both active and reactive power will also oscillate, resulting in both linear and sinusoidal components of p and q as shown in equation 5.

$$\begin{aligned} p &= \tilde{P}_{ac} + \bar{p}_{dc} \\ q &= \tilde{q}_{ac} + \bar{q}_{dc} \end{aligned} \quad (5)$$

The subscript *ac* and *dc* respectively denote oscillating and linear or dc components of both p and q.

To obtimise the power factor, the negative components of $\tilde{P}_{ac}$ and $q$ (i.e., $-\tilde{P}_{ac}$ and $-q$) has to be fed into the system. The value of $\tilde{P}_{ac}$ is obtained through low pass filter (LPF) while the inversion of $q$ gives the required magnitude of $-q$ as shwon in the block diagram. Hence, equations 5 will be modified to,

$$\begin{aligned} p &= -\tilde{P}_{ac} \\ q &= -q \end{aligned} \tag{6}$$

From equation 4, we have:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix}^{-1} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \tag{7}$$

Therefore, the orthogonal components ($\alpha$ and $\beta$) of he reference currents required for controlling the STATCOM inverter switches is:

$$\begin{bmatrix} I_\alpha^* \\ I_\beta^* \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ q \end{bmatrix} \tag{8}$$

Substituting the magnitude of p and q in equation 6, we have:

$$\begin{aligned} &\begin{bmatrix} I_\alpha^* \\ I_\beta^* \end{bmatrix} \\ &= \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix}^{-1} \begin{bmatrix} \tilde{P}_{ac} + p_{loss} \\ -q \end{bmatrix} \end{aligned} \tag{9}$$

$p_{loss}$ is the average power loss due switching operation of the STATCOM's semi-conductor devices. This will ensure a regulated DC bus voltage as shown in the diagram.

The established reference currents in equation 9 are converted to their corresponding 3-phase signals, $I_{abc}^*$ yeilding equation 10. This step is illustrated in the inverse Clark's transformation block in the diagram.

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_\alpha^* \\ I_\beta^* \end{bmatrix} \tag{10}$$

These are the required currents for driving the STATCOM inverter switches (MOSFETs).

**Control of the switching currents ($I^*_{abc}$) using the hystereses technique**

For a steady operation of the inverter switches, ripple-free firing signals are necessary. To achieve this, a reliable and easier control technique known as Hysteresis control shown in figure 4 is selected in this work.

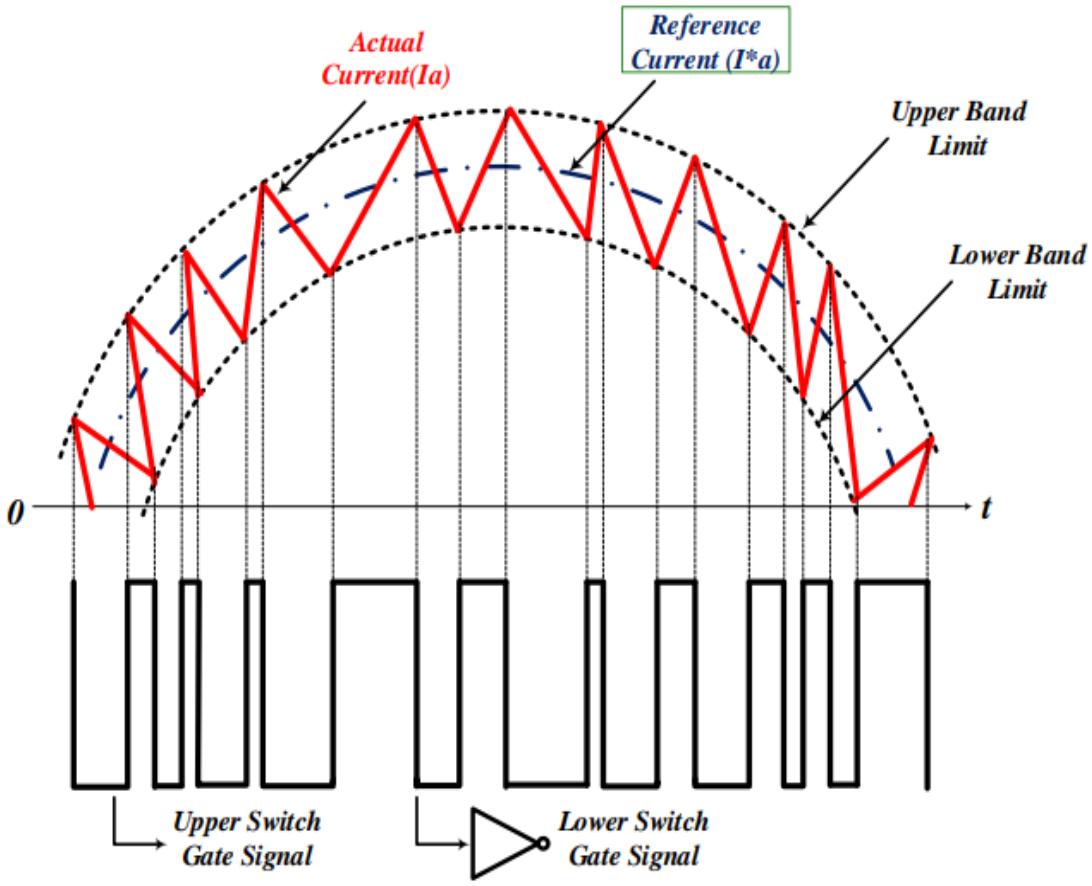



*Figure 4:* ***Semi-sinusoid illustration of Hysteresis current control***

The diagram elaborates a half-cycle sinusoidal signal of one of the phases with a pulse-width modulated signal, switching ON and OFF in a complementary fashion with a bandwidth determined by the hysteresis lower and upper limits, as shown. $I_a$ is the actual inverter switching current and $I_a^*$ is the set (reference) current. For example, when $I_a$ reaches the upper limit, the upper switch opens and the lower switch will instantly close. The reverse is the case when the $I_a$ reaches the lower limit. This process continues to ensure the switching is maintained at the reference current.

**MATLAB Design parameters**

The system is implemented using MATLAB/Simulink software based on the design parameters. This includes the 3-phase supply, and load systems, line parameters, transformers, STATCOM, and its control blocks as shown in the block diagram.

**Table 1: Summary of design parameters**

| Parameter | Description/Rating |
|---|---|
| **3-phase Source** | 11 kV, 50 Hz source feeding a 500 kVA, 11 kV/400 V distribution transformer transformer |
| **System load** | 33kVA |
| **STATCOM inverter rating** | 40kVA minimum |
| **Inverter DC bus voltage** | 650V |
| **Kp, Ki (STATCOM) 1, 25** | |
| **Inverter DC bus capacitor** | 6000 μF |
| **Coupling inductor** | 1.2m H |
| **PID constants: Kp, Ki** | 1, 25 |

**RESULTS AND DISCUSSION**

**Simulation Results**

The Simulink model illustrating four (4) major blocks is shown in fugure 5. The PCC (point of common coupling) is the point at which the STATCOM injects compensation currents for instantaneous reactive power adjustment. Figure 6 through 9 illustrates the Simulink display of the performance of the STATCOM for reactive power compensation under various load conditions. The Fast Fourier Transform (FFT) analyses of the of thesystem harmonics are shown in figure 10 through 13.

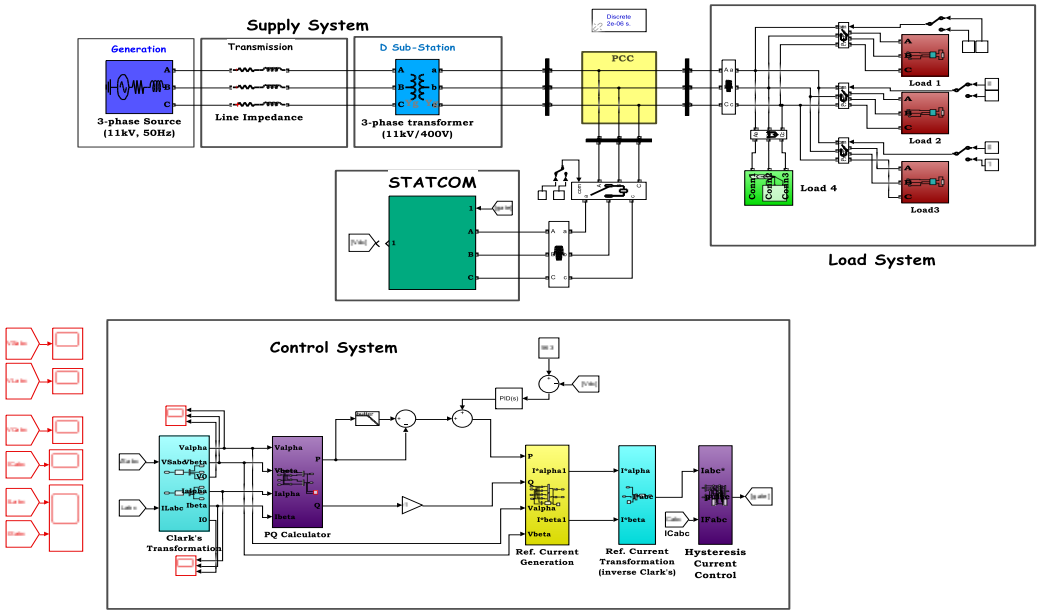



*Figure 5:* ***Simulink model of the complete system illustrating the major sub-systems***

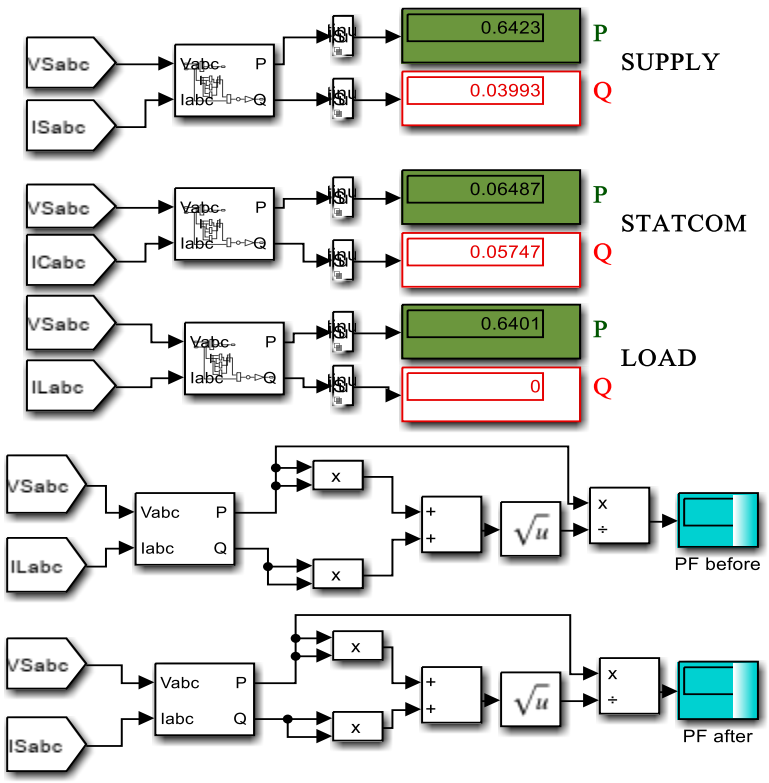
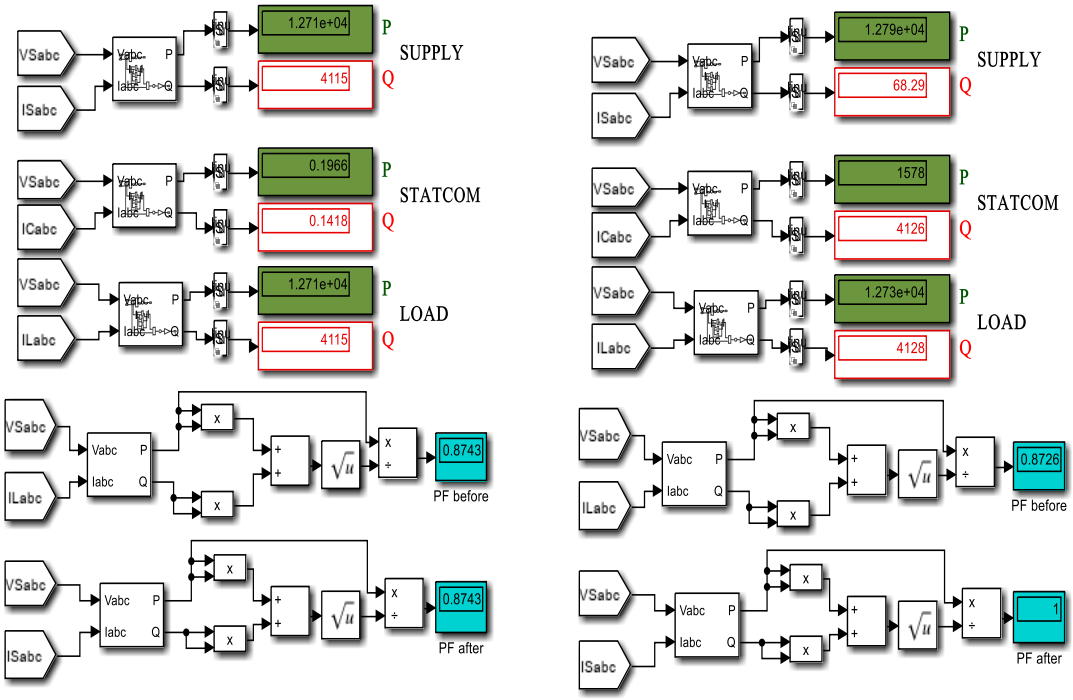
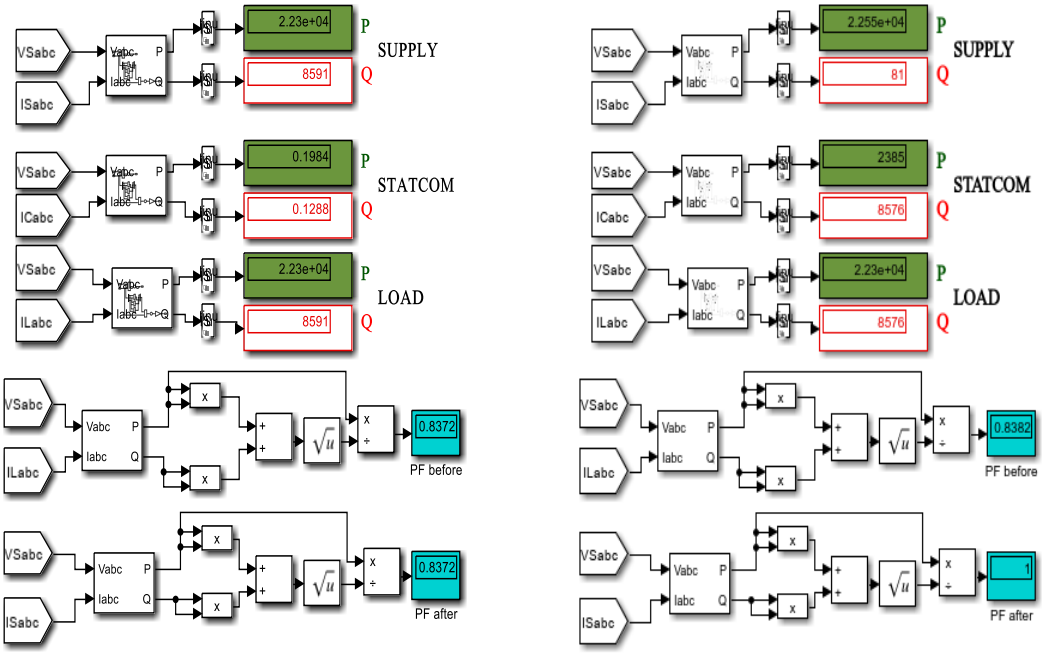



**Figure 6:** Simulink output for a purely resistive load (**load 4**)



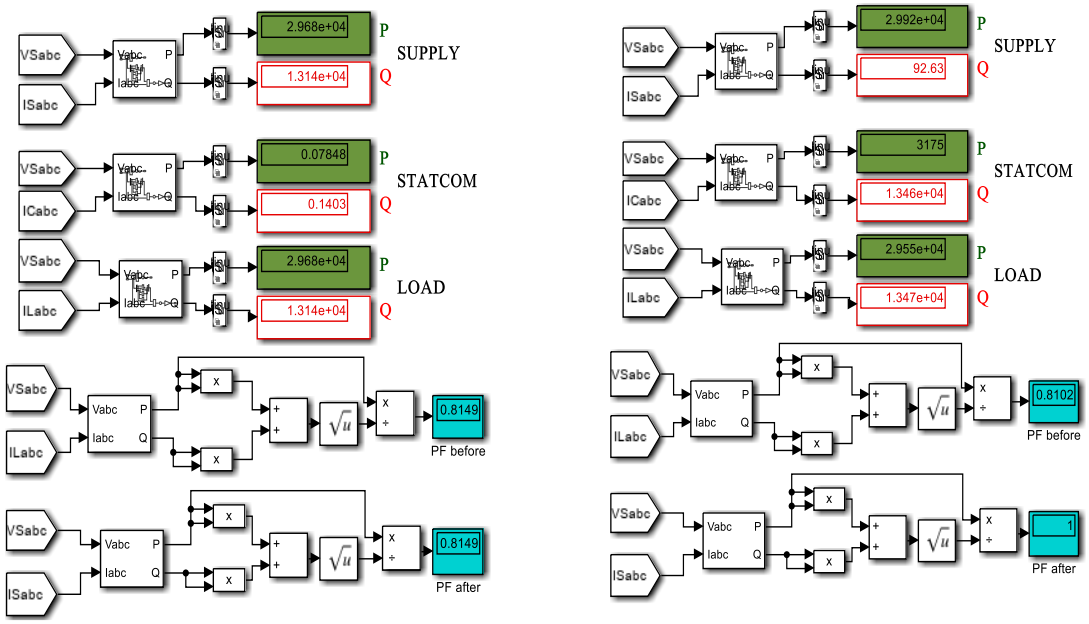

(a) Without STATCOM (b) with STATCOM

**Figure 7:** Simulink output when **load 1** (inductive) is added to the system




(a) Without STATCOM (b) with STATCOM

**Figure 8:** Simulink output when **load 2** (inductive) is added to the system




(a) Without STATCOM (b) with STATCOM

**Figure 9:** Simulink output when **load 3** (inductive) is added to the system

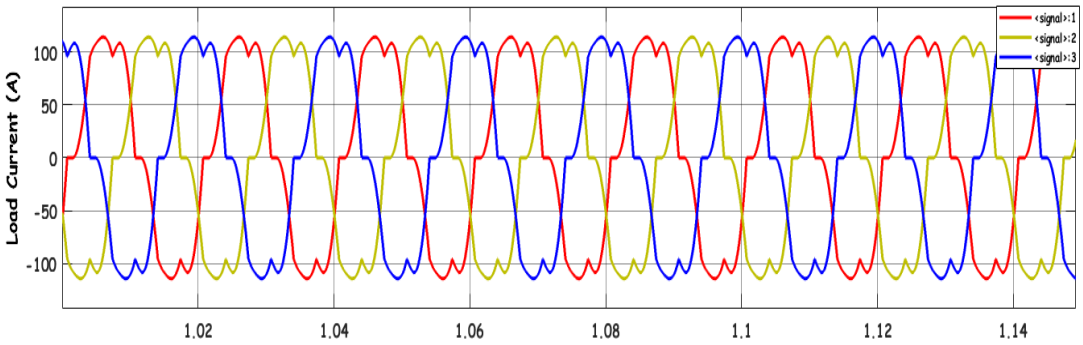



**Figure 10:** distorted signal due to inductive load which would replicate on the source current

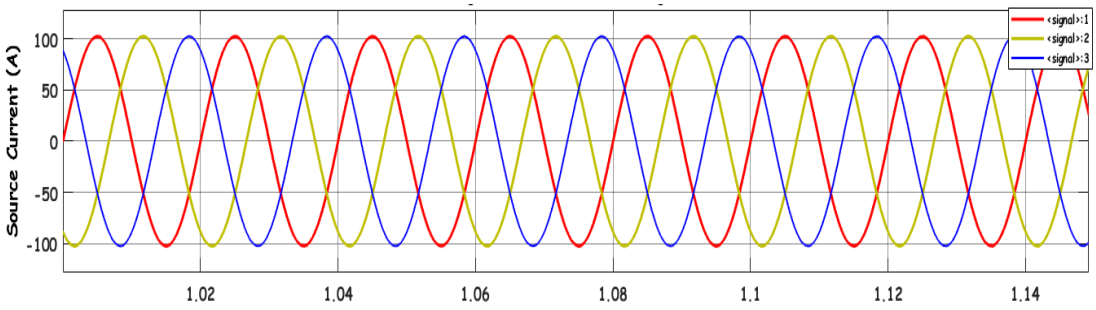



**Figure 11:** compensated source current indicated by a pure sinusoid

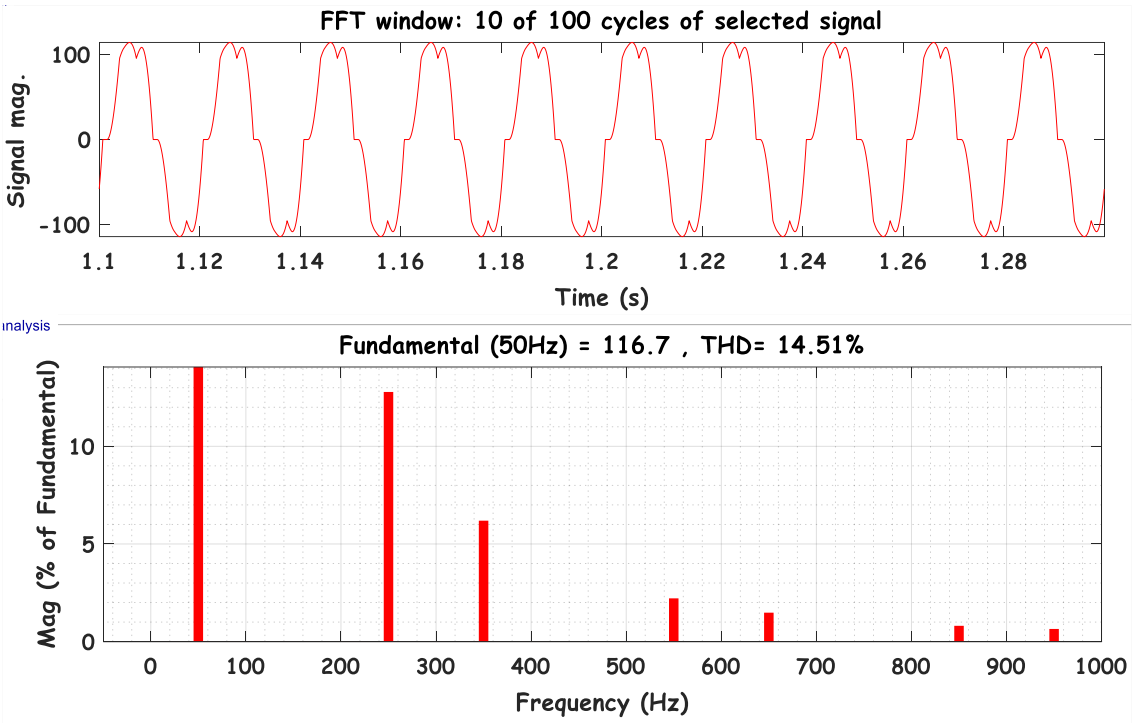



**Figure 12:** FFT analyses on the load currents of figure 10

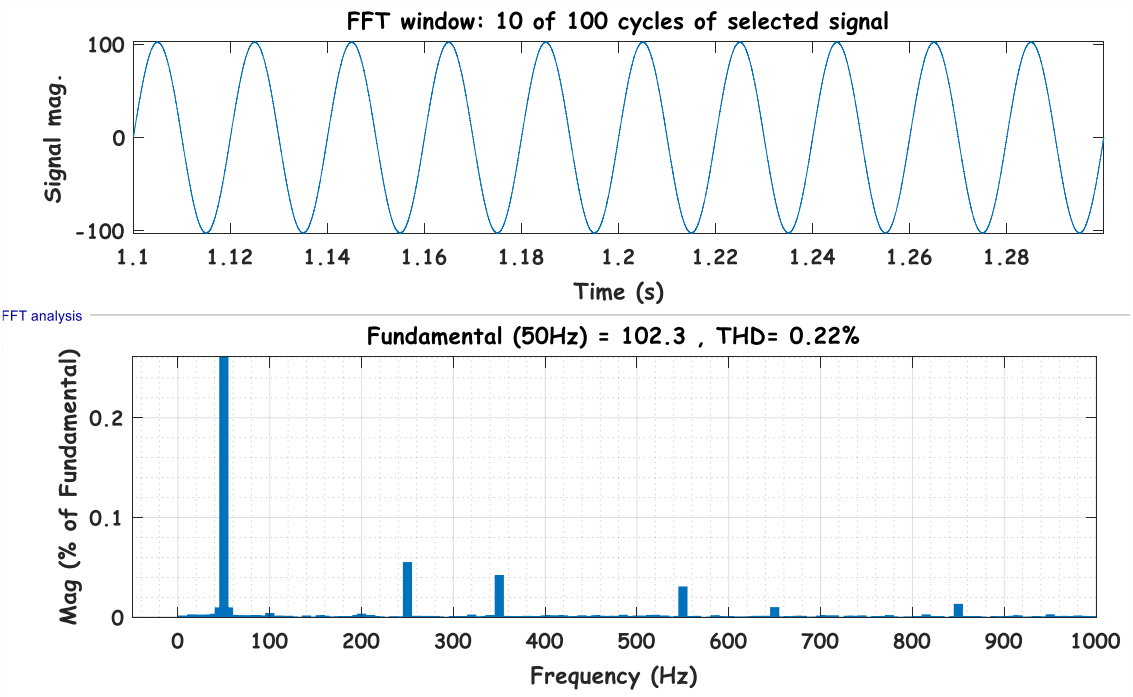



**Figure 13:** FFT analysis on the source current after compensation, shwon in figure 11

**The Comprehensive Summary of the Results**

**Table 1:** the comprehensive summary of the simulink display of figure 6 through 9

| Connected Load | STATCOM Connection | Power Requirement of the load | | Power supply by the source | | STATCOM Compensation | | System Power Factor (PF) | |
|---|---|---|---|---|---|---|---|---|---|
| | | **(W)** | **(Var)** | **(W)** | **(Var)** | **(W)** | **(Var)** | **before** | **after** |
| **4** | No | 0.6401 | **0** | 0.6423 | 0.03993 | 0.06487 | 0.05747 | **1.0** | **1.0** |
| **(Purly resistive)** | | | | | | | | | |
| **4+1** | **No** | 12710 | **4115** | 12710 | **4115** | 0.1966 | 0.1418 | **0.87** | **0.87** |
| **(Inductive)*** | Yes | 12730 | **4126** | 12790 | 68.29 | 1576 | **4126** | **0.87** | **1.0** |
| **4+1+2** | **No** | 22300 | **8591** | 22300 | **8591** | 0.1984 | 0.1288 | **0.84** | **0.84** |
| **(Inductive)*** | Yes | 22300 | **8576** | 22550 | 81 | 2385 | **8576** | **0.84** | **1.0** |
| **4+1+2+3** | **No** | 29680 | **13240** | 29680 | **13140** | 0.07848 | 0.1403 | **0.81** | **0.81** |
| **(Inductive)*** | Yes | 29550 | **13470** | 29920 | 92.63 | 3175 | **13460** | **0.81** | **1.0** |

**Table 2:** the STATCOM performance on the system harmonics based on IEEE519 Standard[1]

| **Harmonic Series** | **Distortions on the supply side** | **Distortions on the load side** | **IEEE 519 Standards (%)** |
|---|---|---|---|
| **THD** | 14.5 | 0.22 | 5.0 |
| **$5^{th}$** | 12.8 | 0.55 | 4.0 |
| **$7^{th}$** | 6.18 | 0.04 | 4.0 |
| **$11^{th}$** | 2.22 | 0.03 | 2.5 |
| **$13^{th}$** | 1.48 | 0.01 | 2.5 |
| **$17^{th}$** | 0.81 | 0.01 | 1.5 |
| **$19^{th}$** | 0.65 | 0.00 | 1.5 |

## DISCUSSION

The STATCOM's performance is verified using four (4) different loads. These include load 1, load 2, load 3 and load 4. Load 4 is purely resistive while loads 1, 2 and 3 are all inductive and are added serially for various incremental reactive power consumptions.

**Load 4 (purely resistive):** Figure 6 shows the output display for this load. In this condition, the reactive power is shown to be 0 Var as expected. Hence, the power factor is ideally 1.0, both before and after the STATCOM action.

**Load 4 + load 1 (inductive):** The load is now considered inductive. In this case, the system is tested under two conditions: when the STATCOM is not connected, figure 7 (a) and when it is connected, figure 7 (b). When it is not connected, the source indicates a reactive power supply of 4115 Var with a power factor of 0.87. This is exactly the reactive power requirement of the load. When the STATCOM is connected, an amount of 4126 Var has been compensated by the STATCOM with an ideal power factor of 1.0, raw 3 of table 1.

**Load 4 + load 1 + load 2 (inductive):** This is shown in figure 8 (a) and (b) for both connected STATCOM and not respectively. When the STATCOM's switch is open, the source is compelled to supply the reactive load requirement of 8591 Var resulting in a power factor of 0.84. When the STATCOM's switch is closed, the STATCOM now balances out with a reactive power of 8576 Var and an improved power factor of 1.0.

**Load 4 + load 1 + load 2 + load 3 (inductive):** This is similar to the previous cases with an incremental reactive load. Figure 9 (a) and (b) show the conditions for both connected STATCOM and not respectively. When the STATCOM is isolated, the source has to supply the reactive load requirement of 13470 Var. When the STATCOM's breaker is closed, the STATCOM detects through a feedback loop and compensates for an approximately equal amount of 13460 Var, readjusting the power factor to unity as summarised in the last row of the table.

Slight discrepancies in both active and reactive power can be observed in each case of the supply, the load and or the STATCOM when the load is changing. this is usually due to Inherent characteristics of the model components, such as slight inductive elements within the circuits.

Figure10 illustrates the 3-phase load current waveforms under the combination of the four load conditions. It can be seen in the figure that the signals contain a severe distortion. This distortion would replicate on the source currents and hence throughout the system. This will have a significant impact on the entire system such as energy lost through components heating, etc. Figure 11 is a corresponding sinusoidal signal waveform of the source currents after the injection of the

compensating signals at the PCC. To evaluate this, Fast Fourier Transform (FFT) analyses are performed both before and after STATCOM's action. These are shown in figure 12 and 13 respectively .

The summary of these analyses is contained in table 2. The Total harmonic distortion (THD) and the harmonic sequences ranging from $5^{th}$ to $19^{th}$ are recorded in column 1 except zero sequence harmonics such as $3^{rd}$, $9^{th}$ and $15^{th}$ which only exist in a 3-phase. 4-wire systems. The analyses revealed that the THD, $5^{th}$ and $7^{th}$ harmonics have gone beyond the IEEE 519 limits (as seen in column 2). However, after connecting the STATCOM, these harmonics (shown in column 3) have been cleaved to the lowest fractions.

## CONCLUSION

Using MATLAB/Simulink software, a model of a static synchronous compensator (STATCOM) with a control based on an instantaneous reactive power theory (IRPT) has been realized.

Within the limits of the system and modeling errors, the model STATCOM can sense and instantly generate an equivalent amount of a reactive power requirement of the load. Hence, an ideal power factor of unity has been realized with three different levels of reactive power.

Under a heavy reactive load condition, a sinusoidal signal with a total harmonic distortion (THD) of less than 1% has also been achieved.

## RECOMMENDATION

The power supply source is not capable of making an instant adjustment to the load changes leading to slight errors in the MODEL performance. Further study may design additional circuit for an improved performance.

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