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Effect of Capacitor Switching on Reactive Power Control in Electrical Distribution Network

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Abstract

In electrical distribution network, load varies over the day, with very low load from midnight to early morning and peak values occurring in the evening due to the load demand by the consumer. This variation in load demand leads to variation in reactive power because most loads are inductive especially in industries where three phase industrial motors are used. In addition, Furthermore, the variation in reactive power affects current flow through the lines, transformers, generators and cause power losses in distribution network. Hence, there is the need to ensure reliable energy distribution even in the presence of load and reactive power variations. This research paper applied shunt switching capacitor for reactive power control of electrical distribution network using 11 kV distribution network located at Monatan, Ibadan, Oyo State Nigeria as a case study. Hourly load data of the network were collected to determine the reactive power of the network for stability evaluation. Capacitor Switching Compensation was incorporated into distribution network using KCL algorithm as power flow to form Capacitor Switching Compensation Model (CSCM) to improve the reactive power of the distribution network and simulation was carried out in MATLAB environment. The results showed that reactive power of the distribution network was 3.1$\pm sd$ MVAR. The CSCM improved the reactive power to 52 %. The study showed that incorporating capacitor switching as a compensation technique enhances the stability of the distribution network.

Keywords: Electrical Distribution Network, Reactive Power, Capacitor Switching Compensation Model, Power Loss, Load Data, MATLAB.
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1. Introduction

Electrical energy is generated, transmitted, distributed and utilized as Alternating Current (AC). However, there are several disadvantages of Alternating Current. One of these is the necessity of reactive (imaginary) power that needs to be supplied along with active (real) power. Reactive power is either generated or consumed. The impedance of a branch of circuit in an AC framework comprises of two parts, resistance and reactance. Reactance can either be inductive or capacitive, which adds to reactive power in the circuit [1], [10]. Reactive power neither consumes nor supplies energy. The reactive power is estimated in volt-ampere reactive (VAR). As the length of a line builds, its inductive reactance increases and then there is more capacitive reactive power expected to counterbalance the impact and to keep up satisfactory voltage [2].

In addition, if the AC circuit contains reactance, there is power component associated with the magnetic and/or electric fields. The power associated with these fields is not consumed as it is in a resistive circuit, but rather stored and then discharged as the alternating electric current/voltage goes through its cycle [6]. Reactive power is the electrical energy that is needed to energize the portions of the power system that behaves like capacitor (the overhead conductors that are continuously charged and discharged by the AC waveform); and inductors (electric motors and transformers which store a considerable amount of energy in magnetic field that are essential for device operation) [3], [4].

Apparent power is real (active) power plus reactive power. A related concept is that of power factor (magnitude of active power divided by magnitude of apparent power). In the electric power industry, if the power factor is too low (under 0.85) due to the magnitude of the reactive component, corrective actions are usually taken [5]. In many cases, utility system operators charge power factor penalties if a facility is consuming too much reactive power. Significant reactive power is required to maintain voltage and power factor within the operating limits prescribed by the power grid entity that supplies power to the grid. However, applying proper power factor correction methods compensate the effect of reactive loads of the system and hence improve the system's overall efficiency [13], [15].

Reactive power can be leading or lagging. Under light load or open line, there is high voltage; but if the system is heavily loaded (at lagging power factor) the voltage is reduced. Capacitors are connected to minimize the losses and voltage drops. Since most loads are inductive and consume lagging reactive power, the compensation required is usually supplied by leading reactive power. This can be employed either at load level in the distribution network, substation level or at transmission level using capacitors. It is economical to supply this reactive power closer to load in the distribution network [6]. [10].

The purpose of reactive power control is to maintain acceptable standard at the service entrance of all consumers served by the feeder under all possible operating conditions. Electric utilities traditionally maintain distribution network load variation by reducing the amount of reactive power flowing on the distribution feeder thereby reducing electrical losses along the feeder using different methods. Without such adjustments, reactive power at one end of some feeders might sag to unacceptable low levels at peak periods, while reactive power close to the substation might rise to unacceptably high levels at minimum load [7], [12]. From the above view, this research paper intends to address reactive power control on power distribution network using capacitor switching.

1.1 Distribution Network

Distribution network is the medium through which electric power is conveyed in bulk from the power station to the various end users [8], [9]. The physical structure of most power system consists of generation facilities feeding bulk power into a high-voltage bulk transmission network that in turn serves any number of distribution substations. A typical distribution substation will serve from one to as many as ten feeder circuits. A typical feeder circuit may serve numerous loads of all types as shown in Figure 1. A light to medium industrial customer may take service from the distribution feeder circuit primary, while a large industrial load complex may take service directly from the bulk transmission system. All other customers, including residential and commercial, are typically served from the secondary of distribution transformers that are in turn connected to a distribution feeder circuit [9], [10].

It holds a very significant position in the power system since it is the main point of the line between bulk power and consumers and it contributes to about 2-3 % of the total losses in power systems [7]. The distribution network is usually designed to operate at specified power capability and voltage level. Operating outside the allowable tolerances of these values affect the quality of power reaching the consumers of electricity [2], [8], [11].

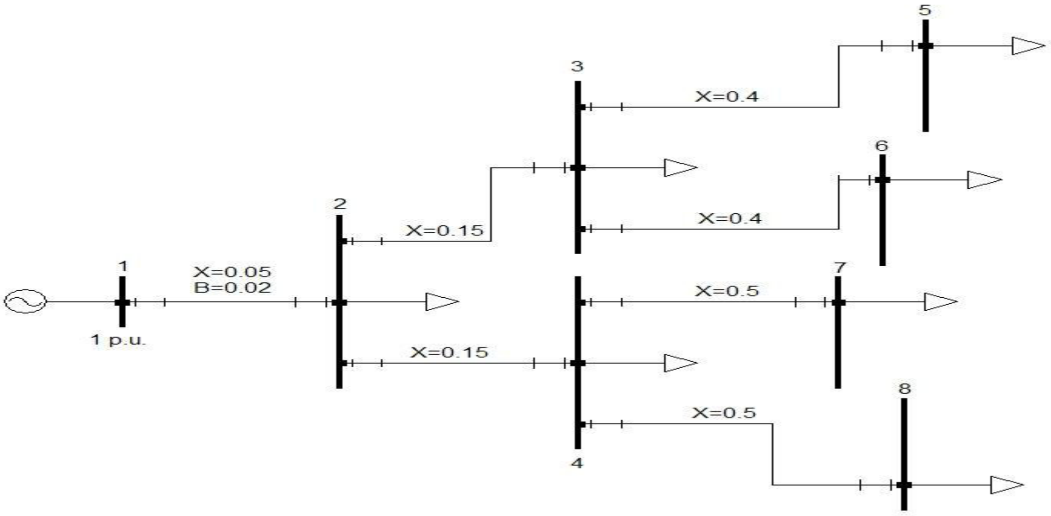

Figure 1: A simple Distribution Network

1.2 Monatan 33/11 kV, 7.5 MVA Distribution Substation

The Monatan 33/11 kV, 7.5 MVA distribution substation of Ibadan Electricity Distribution Company (IBEDC) Plc, Monatan Business Unit, Ibadan, Oyo State, Nigeria fed from Ibadan North–Adogba 132/33 kV, 30 MVA Transmission substation used as case study in this study is as shown in Figure 2 [1], [2].

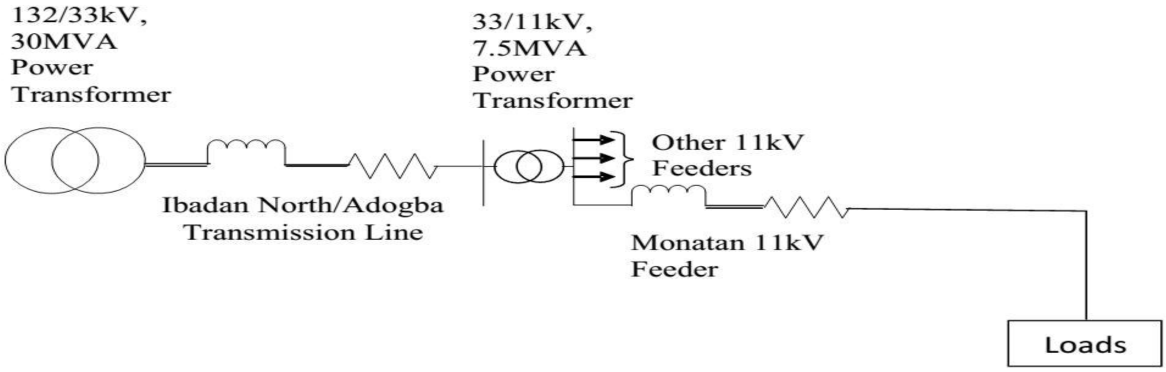

Figure 2: Single Line Diagram of Power Transformers and Monatan 11 kV Feeder

1.3 Reactive Power Control

The high demand of reactive power increases the reactive output of generators. When generator hits the reactive power limit, its terminal voltage decreases. A lot of reactive power demand is then transferred to another generator further far from critical area. This will prompt cascading over-loading of generators. The strategy will in the long run lead to system collapse, possibly leading to loss of synchronism of generating units and a major blackout. For efficient and reliable operation of power system, the control of reactive power should be minimized so as to reduce I^2R and I^2X losses. This ensures the transmission system operating basically for real power [1], [5], [12], [14], [17].

The power system supplies power to a vast number of loads and is feeding from many generating units. There is an issue of maintaining reactive power within required limits. As load changes, the reactive power requirements of the transmission system vary. The reactive power cannot be transmitted over long distance and across large power angles, even with significant voltage sizes. Real losses should be minimized for economic reasons and reactive losses ought to be minimized to reduce investments in reactive power devices. Both active and reactive losses depend on reactive power transfer [13], [11]. Hence there is the need to minimize losses and the need to minimize reactive power transfer in the network.

1.4 Reactive Power Compensation

[11] analyzed the requirement for reactive power compensation. It is prudent to supply this reactive power nearer to the load in the distribution system . Reactive power compensation is frequently the best approach to improve both power transfer capacity and voltage stability [10]. Reactive compensation can be divided into series and shunt compensation. It can likewise be divided into active and passive compensation. Shunt capacitors and reactors as well as series capacitors give passive compensation. They are either permanently connected to the transmission and distribution system or switched. They contribute to voltage control by modifying the network characteristics [18], [20]. When designing a compensation scheme, attempt should be made to accomplish the most economical solution in which the saving accomplished in the equipment cost is essentially more prominent than the procurement cost of the reactive power [14], [21].

According to [9], the performance of power lines can be improved by reactive compensation of a series or parallel type. It has been examined that the percentage compensation is in the range of 25 to 75 percent [19]. In addition, it was stated that line compensation can be done in several ways. Shunt reactors are widely used to reduce high voltage under light load or open line conditions. If the system is heavily loaded, shunt capacitors, static var control and synchronous condensers are used to improve voltage, increase power transfer and improve the system stability [19].

[21] examined an assessment of reactive power control devices in distribution networks.. The recent trend towards Distributed Energy Resources (DERs) and Distributed Generation (DG), in particular, is often based on the rationale to support compensate for reactive power closer to the end users. This situation calls for a systematic approach to assessing alternatives for reactive power control, both old and new.

1.5 Shunt Capacitors

Shunt capacitor banks are always connected to the bus rather than to the line. They are connected either directly to the high voltage bus or to the tertiary winding of the main transformer. Shunt capacitor banks are breaker-switched either automatically by voltage relays or manually [10]. The capacitor requirement is developed on a per-transformer basis. The ratio of the kvar connected to kVA per feeder, the position on the feeder of existing capacitor banks and any concentration of present or future load are all considered in determining the position of the new capacitor banks. The feeder type at the location of the capacitor bank determines if the capacitor will be pole-mounted (overhead) or pad-mounted (underground). Substation capacitor banks (three or four per transformer) are usually staged to come on and go off at specific load levels [16], [7].

Thousands of capacitor banks are installed in the entire distribution network. The primary usage for capacitor banks in the distribution system is to maintain a certain power factor at peak loading conditions. The target power factor is 0.98 leading at system peak. This was set as an attempt to have a unity power factor on the 69 kV side of the substation transformer. The leading power factor compensates for the industrial substations that have no capacitors. The unity power factor maintains a balance with other utilities. The objective of power factor correction is to provide reactive power close to point where it is being consumed, rather than supply it from remote sources [10], [19].

Compensating the load lagging power factor with the bus connected shunt capacitor bank improves the power factor and reduces current flow through the lines, transformers, generators, etc. This will reduce power losses (I^2R losses) in this equipment [11]. Shunt compensation with capacitor banks reduces kVA loading of lines, transformers and generators, which means with compensation they can be used for delivering more power without overloading the equipment. Shunt capacitors have no moving parts, unlike some other devices used for the same purpose [18].

1.6 Series Capacitor Bank

A series capacitor bank consists of a capacitor bank, overvoltage protection system and a bypass breaker, all elevated on a platform, which is insulated for the line voltage. The overvoltage protection comprises of a zinc oxide varistor and a triggered spark gap, which are connected in parallel to the capacitor bank and a damping reactor. Prior to the development of the high-energy zinc oxide varistor in the 1970s, a silicon carbide nonlinear resistor was used for overvoltage protection [11]. Silicon carbide resistors require a spark gap in series because the non-linearity of the resistors is not high enough. The zinc oxide varistor has better non-linear resistive characteristics, provides better protection and has become the standard protection system for series capacitor banks [18].

The capacitor bank is usually rated to withstand the line current for normal power flow conditions and power swing conditions. It is not economical to design the capacitors to withstand the currents and voltages associated with faults. Under these conditions capacitors are protected by a Metal Oxide Varistor (MOV) bank. The damping reactor (D) will limit the capacitor discharge current and damps the oscillations caused by spark gap operation or when the bypass breaker is closed [12], [15].

[3],[17]] explained that series capacitor when radially connected to the transmission lines from the generation nearby, can create a Sub-Synchronous Resonance (SSR) condition in the system under some circumstances. SSR can cause damage to the generator shaft and insulation failure of the windings of the generator. The ability to vary the series compensation will give more control of power flow through the line and can improve the real stability limit of the power system. Varying the series compensation by switching with mechanical breakers is slow, which is acceptable for control of steady-state power flow. However, for improving the real stability of the system, series compensation has to be varied quickly. This can be accomplished by thyristor controlled series compensation (TCSC) [18, [21].

2. Materials and Method

The use of capacitor switching was considered in this research paper to combat reactive power variation on power distribution system. The technique is one of the prominent methods such as static var control and synchronous condenser that can be used to solve reactive power variation. It provides reactive power control to compensate for reactive power losses when large inductive loads occur. Capacitor switching was chosen because it is less expensive, easy to maintain and needs no additional protective equipment.

One day hourly recorded load data from Monatan 11 kV distribution injection substation of Ibadan Electricity Distribution Company (IBEDC) Plc were obtained to determine the reactive power of the network for stability evaluation. Capacitor Switching Compensation (CSC) was incorporated into the network using KCL algorithm to form Capacitor Switching Compensation Model (CSCM) in order to improve the reactive power of the network and simulation was carried out in MATLAB environment.

Consider Monatan 11 kV distribution feeder with capacitor switching shown in Figure 3. The network is represented by their equivalent models where impedance had been converted to per unit admittances on a common MVA base. 0.8 was chosen as the base power factor at peak period and 0.95 with capacitor installation.

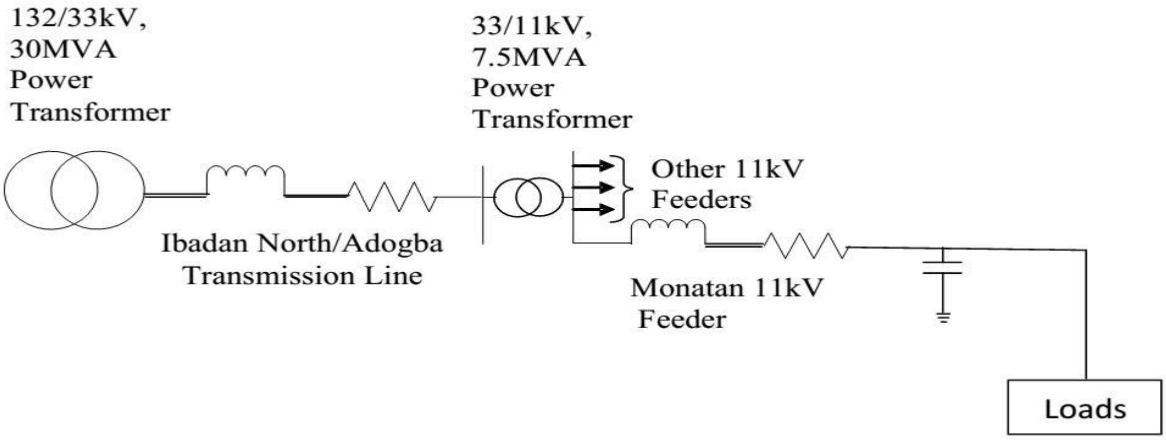

Figure 3: Single Line Diagram of Monatan 11kV Feeder Connections with Capacitor Bank

With the application of KCL, the current entering bus without capacitor placement is given as:

$$I_{ij} = \sum_{j=1}^{n} Y_{ij} V_{ij} \tag{1}$$

The complex power injected by the source into the bus of a power system is:

$$S_i = P_i + jQ_i = V_i I_i^* \tag{2}$$

Therefore;

$$I_i = \frac{P_i - jQ_i}{V_i^*} = \frac{S_i^*}{V_i^*} \tag{3}$$

In polar form, the voltage magnitude is given as:

$$V_i = |V_i| < \delta_i = |V_i| \left(\cos \delta_i + j \sin \delta_i\right) \tag{4}$$

The real and reactive power are given as

$$P_i = V_i \sum_{j=1}^{n} V_j Y_{ij} \cos\left(\theta_{ij} + \delta_j - \delta_i\right) \tag{5}$$

$$Q_i = - V_i \sum_{j=1}^{n} V_j Y_{ij} \sin\left(\theta_{ij} + \delta_j - \delta_i\right) \tag{6}$$

The total power loss in the network is given as:

$$S = \sqrt{P_{LT}^2 + Q_{LT}^2} \quad \text{in MVA} \tag{7}$$

However, with application of capacitor switching on the distribution network, the feeder current is given as:

$$I_i = \frac{\sqrt{P^2 + (Q - Q_c)^2}}{V_i^*} \tag{8}$$

The voltage magnitude (V) when capacitor is used is given as:

$$V_{new} = \frac{S_{new}}{P} X\, V_{old} = \frac{V_{old}}{PF_{new}} \tag{9}$$

The reactive power (Q) when capacitor is used is given as:

$$Q_{new} = \sqrt{S_{new}^2 - P^2} \tag{10}$$

The total active power loss and reactive power loss is given as:

$$P_{LT(C)} = \sum_{i=1}^{n} I_{i(C)}^2 R_i \tag{12}$$

$$Q_{LT(C)} = \sum_{i=1}^{n} I_{i(C)}^2 X_i \tag{13}$$

The total power loss of the network after compensation is given as:

$$S_{(C)} = \sqrt{P_{LT(c)}^2 + Q_{LT(c)}^2} \quad \text{in MVA} \tag{14}$$

where :

Q_c is the reactive power injected by the capacitor in MVAR
I_c is the current injected by the capacitor
X_c is the reactance of the capacitor
P_{LT} is the total active power loss in MW
Q_{LT} is the total reactive power loss in MVAR
I_i is the magnitude of current in Amps

R_i is the resistance of branch i in (Ω/km/phase)
X_i is the reactance of branch i in (Ω/km/phase)
Y is the admittance of the line
V_i is the voltage at bus i
I_i^* is the complex conjugate of source current I_i injected into the bus i
P_i is the real power at bus i
Q_i is the reactive power at bus i
S_{new} is the apparent power when capacitor is used
S_{old} is the apparent power when capacitor is not used
Q_{new} is the reactive power when capacitor is used
V_{new} is the voltage when capacitor is used
V_{old} is the voltage when capacitor is not used
P is the active power
$P_{LT(C)}$ is the total active power loss after compensation in MW
$Q_{LT(C)}$ is the total reactive power loss after compensation in MVAR
$I_{i(C)}$ is the magnitude of current in Amps after compensation

The kVAr capacity of the capacitor required to carry out full compensation of the network was determined as in equation (15).

$$kVAr \text{ required} = P(\tan \emptyset_1 - \tan \emptyset_2) \tag{15}$$

$$kVAr \text{ required} = 96100\ kW\ (0.75 - 0.325)$$

$$= 96100\ kW\ (0.4213)$$

$$= 40487 kVAr$$

$$= 41 MVAr$$

This size corresponds to value obtained from (BICC, 1965) tables for determining sizes of capacitor in kVAr per kW of load of raising the power factor. Therefore this research paper installed 41MVAr capacitor to improve power factor to 95%. In addition, the μF capacity of the capacitor required to carry out full compensation of the network is given as;

$$C = \frac{1}{2\pi f X_c} = 1183.6\ \mu F \tag{16}$$

3. Discussion of Results.

The results of Monatan 11 kV distribution injection substation of Ibadan Electricity Distribution Company (IBEDC) Plc primary radial feeder from the existing 33 kV functioning feeders in Adogba Power Transmission station for reactive power control were analysed and presented without and with capacitor compensation.

3.1 Simulated Results without Capacitor

Figure 4 to Figure 7 presented the bar charts when the active power, reactive power, load (MVA), calculated load current were plotted against time without compensation. It was observed that in Figures 4, 5, 6 and 7, the active power, the reactive power, the load and the calculated load angle varied appreciably with. Figure 8 to Figure 10 showed the bar charts when the load in MVA was plotted with the active power, reactive power and calculated load current (loss) without compensation. The observation was that as load in MVA increased, the active power, reactive power and the calculated load current also increased.

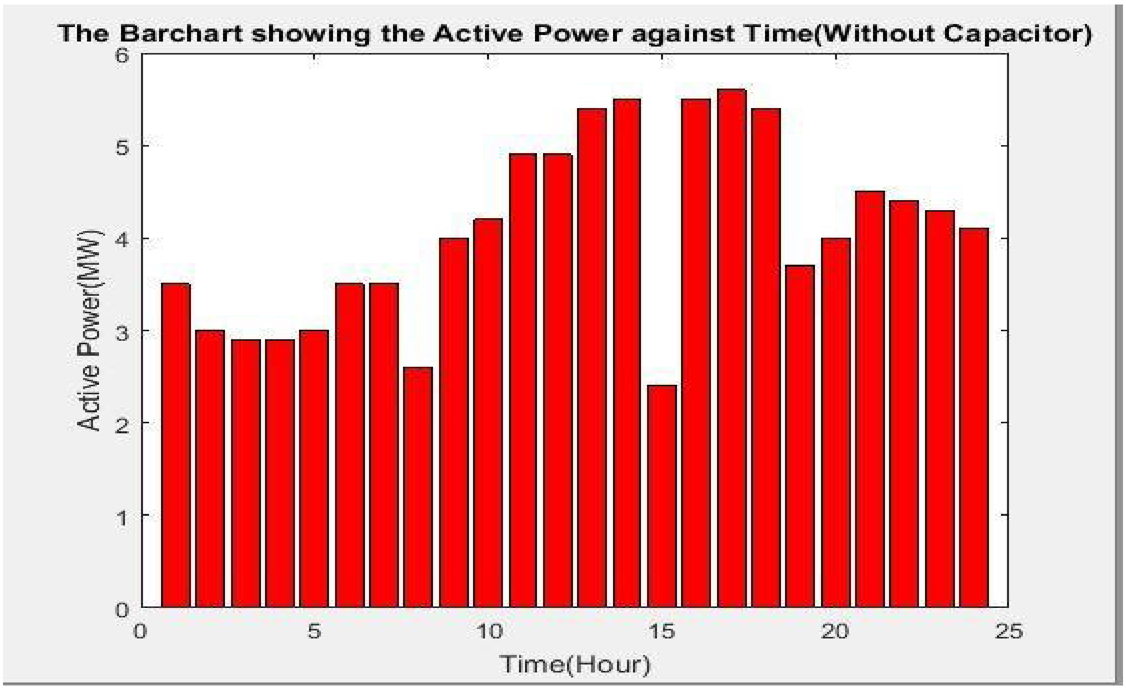

Figure 4: Bar Chart of Active Power against Time without Capacitor

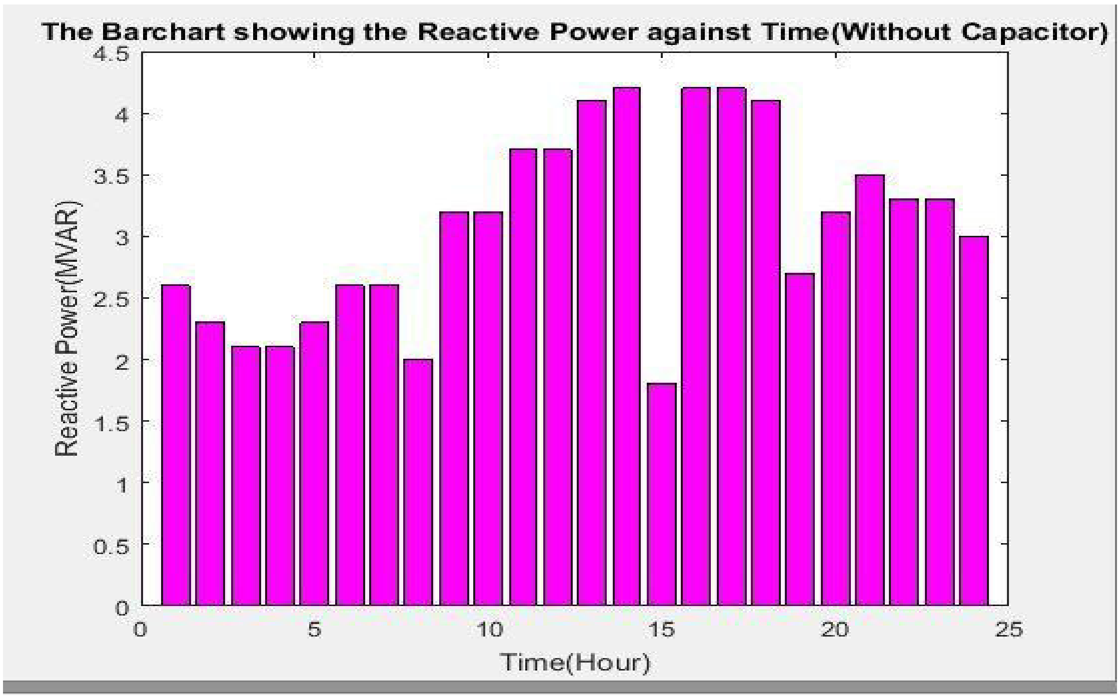

Figure 5: Bar Chart of Reactive Power against Time without Capacitor

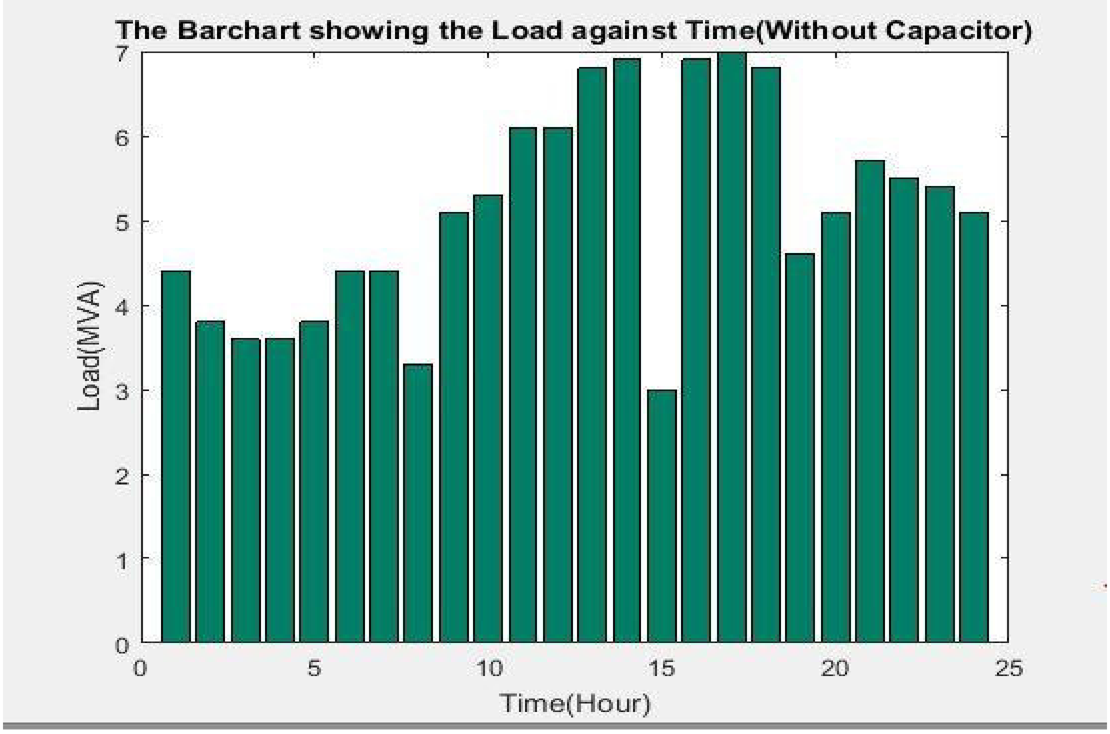

Figure 6: Bar Chart of Load against Time without Capacitor

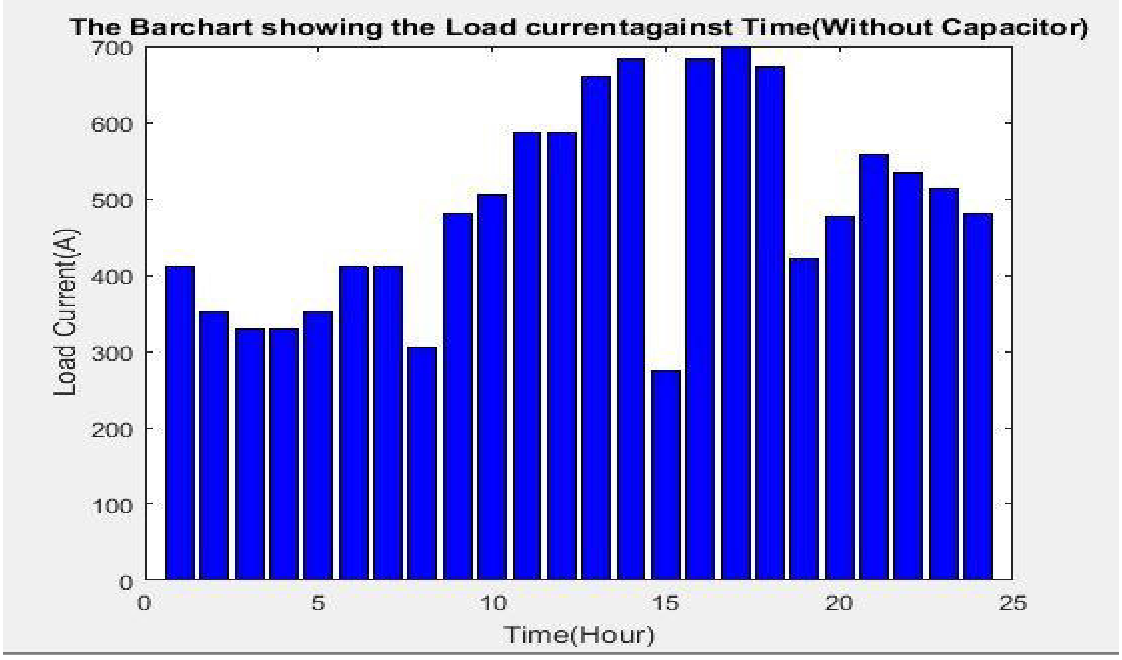

Figure 7: Bar Chart of Calculated Load Current against Time without Capacitor

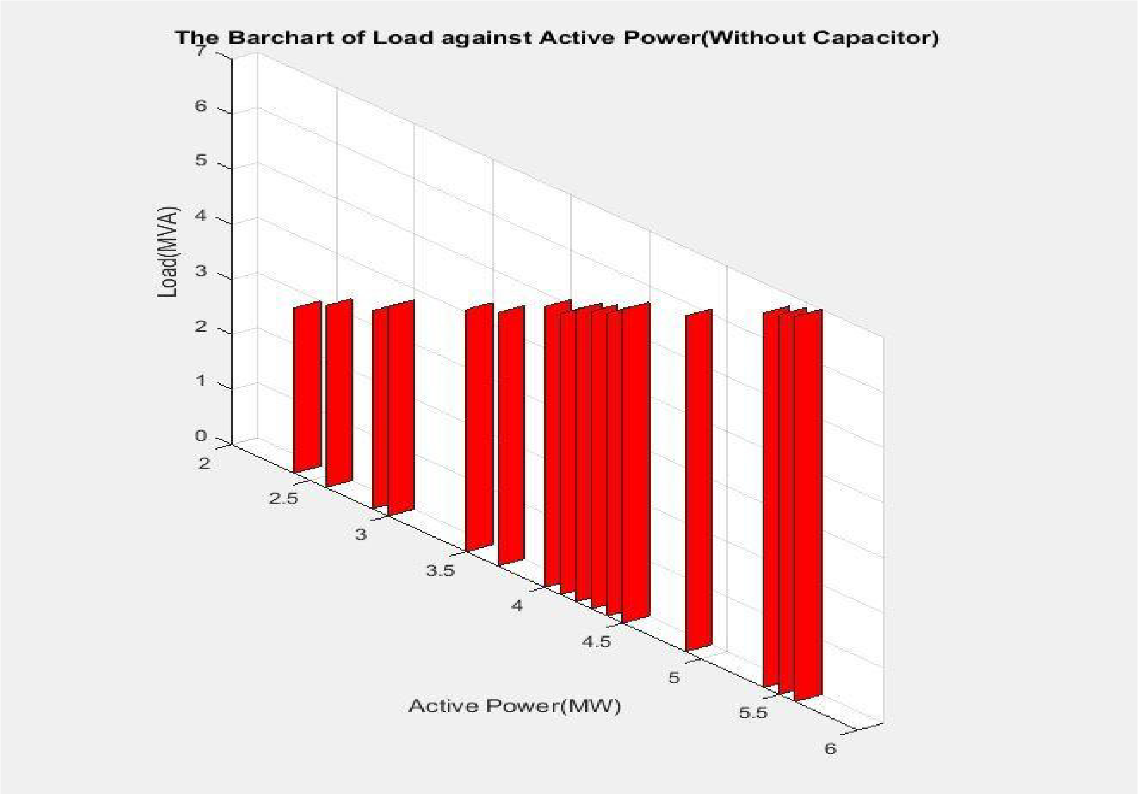

Figure 8: Bar Chart of Load against Active Power without Capacitor

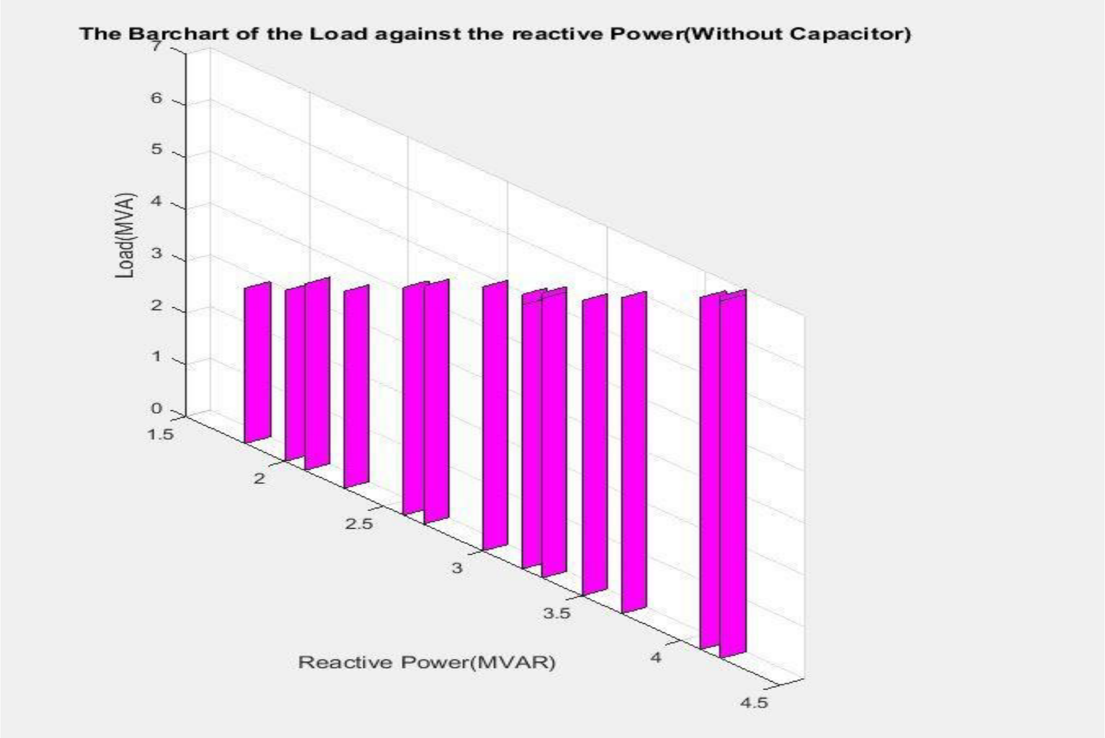

Figure 9: Bar Chart of Load against Reactive Power without Capacitor

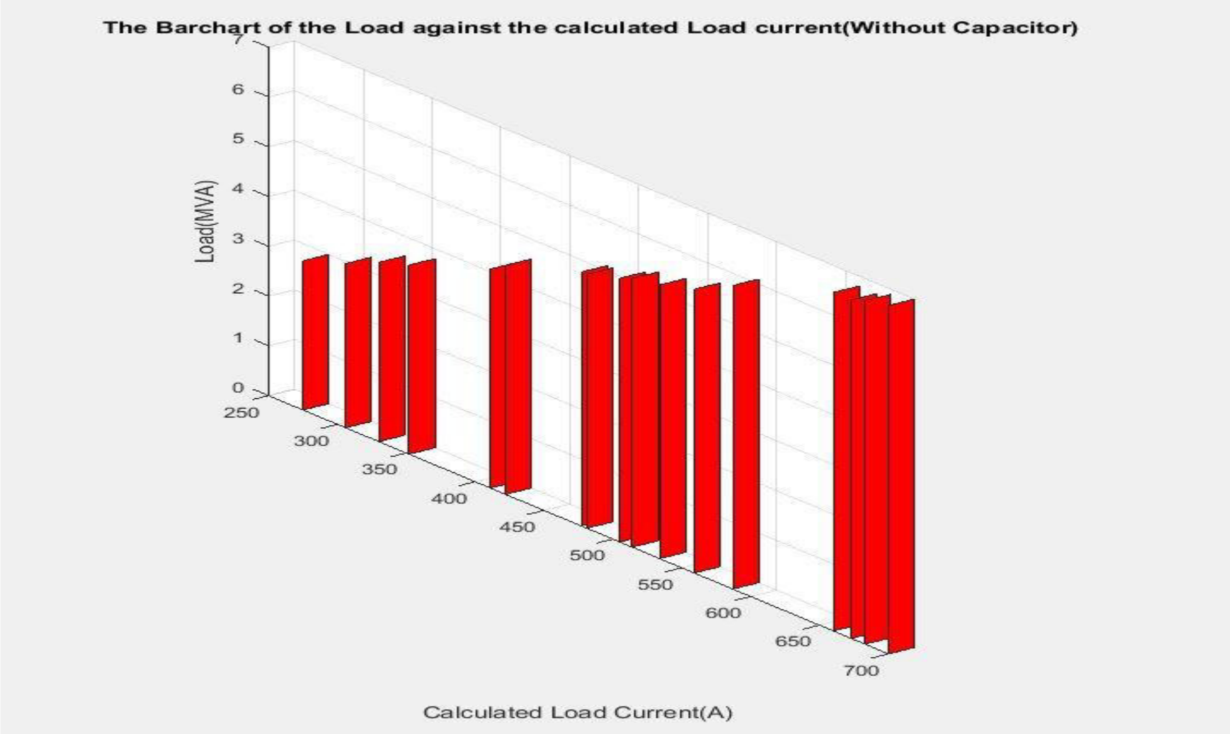

Figure 10: Bar Chart of Load against Calculated Load Current without Capacitor

3.2 Simulated Results with Capacitor

Figure 11 to Figure 14 were the plots for the active power, reactive power, load (MVA) and calculated load current with time respectively when capacitor was used. The bar charts revealed that reactive power and current decreased with time compared to when no compensation was used. Figures 15 to 17 showed the bar charts when the load in MVA was plotted with the active power, reactive power and calculated load current respectively with compensation. It was observed that the active power, reactive power and calculated load current decreased respectively.

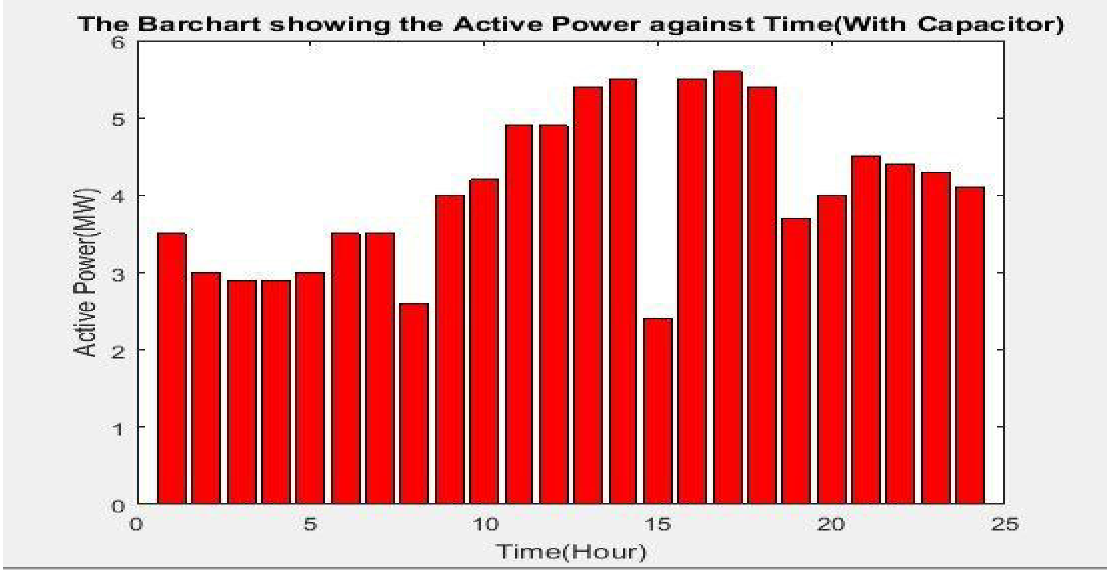

Figure 11: Bar Chart of Active Power against Time with Capacitor

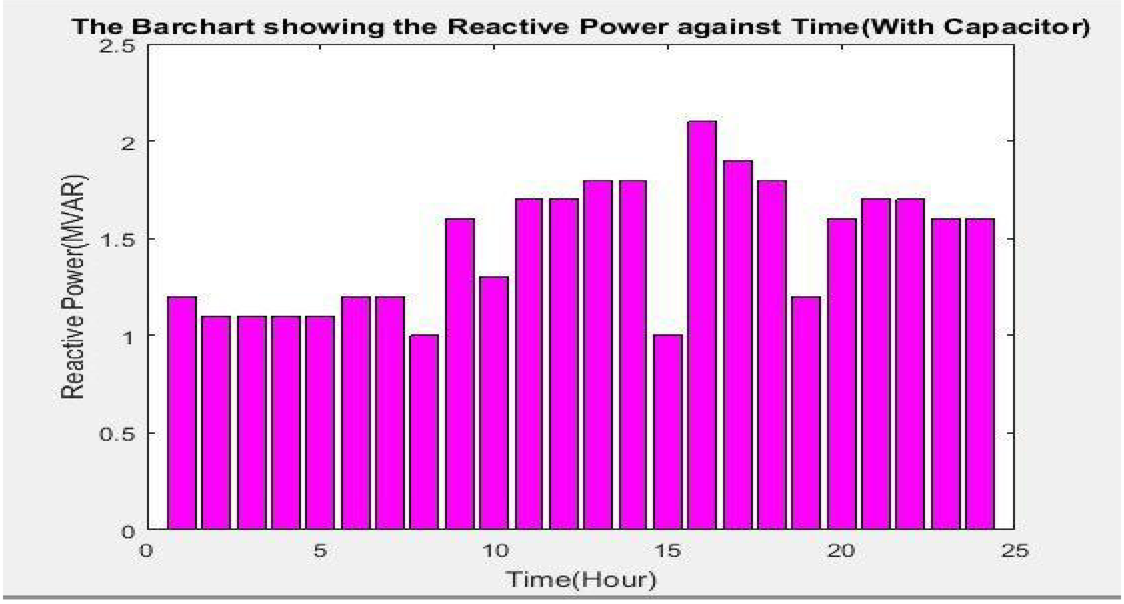

Figure 12: Bar Chart of Reactive Power against Time with Capacitor

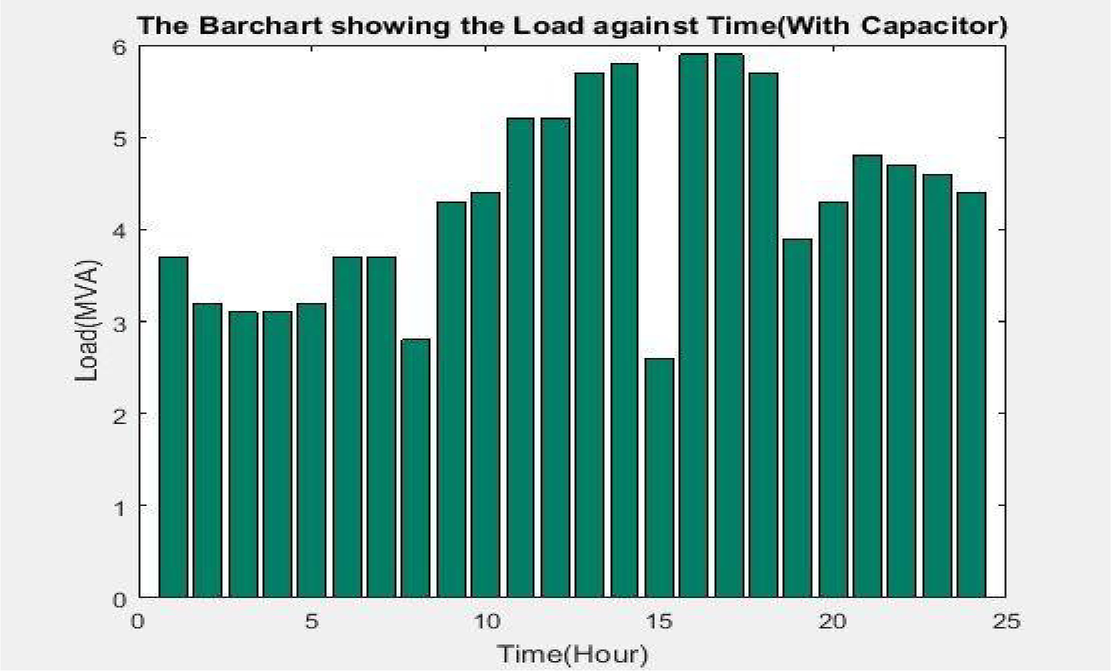

Figure 13: Bar Chart of Load against Time with Capacitor

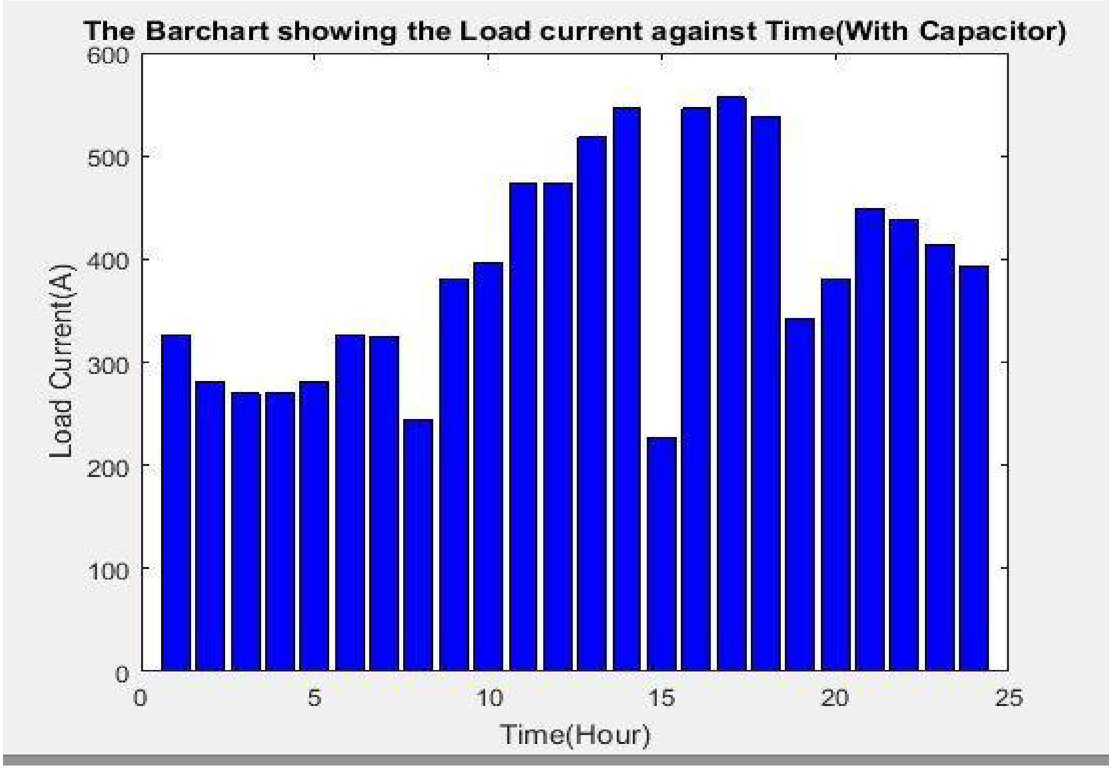

Figure 14: Bar Chart of Calculated Load Current against Time with Capacitor

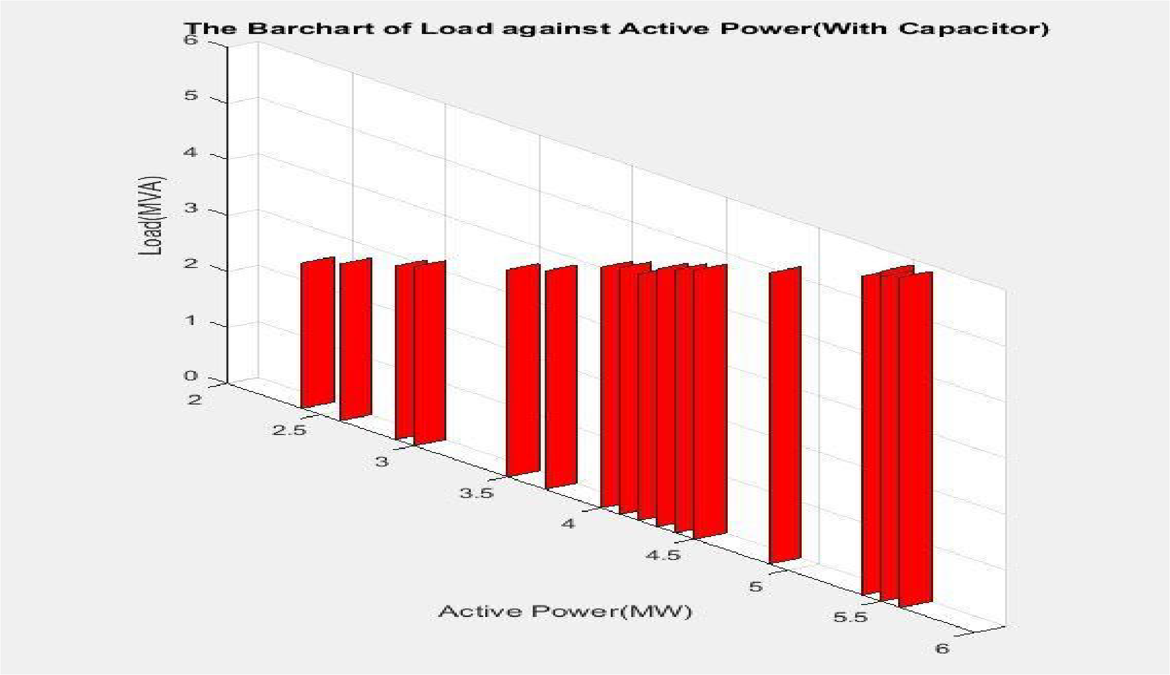

Figure 15: Bar Chart of Load against Active Power with Capacitor

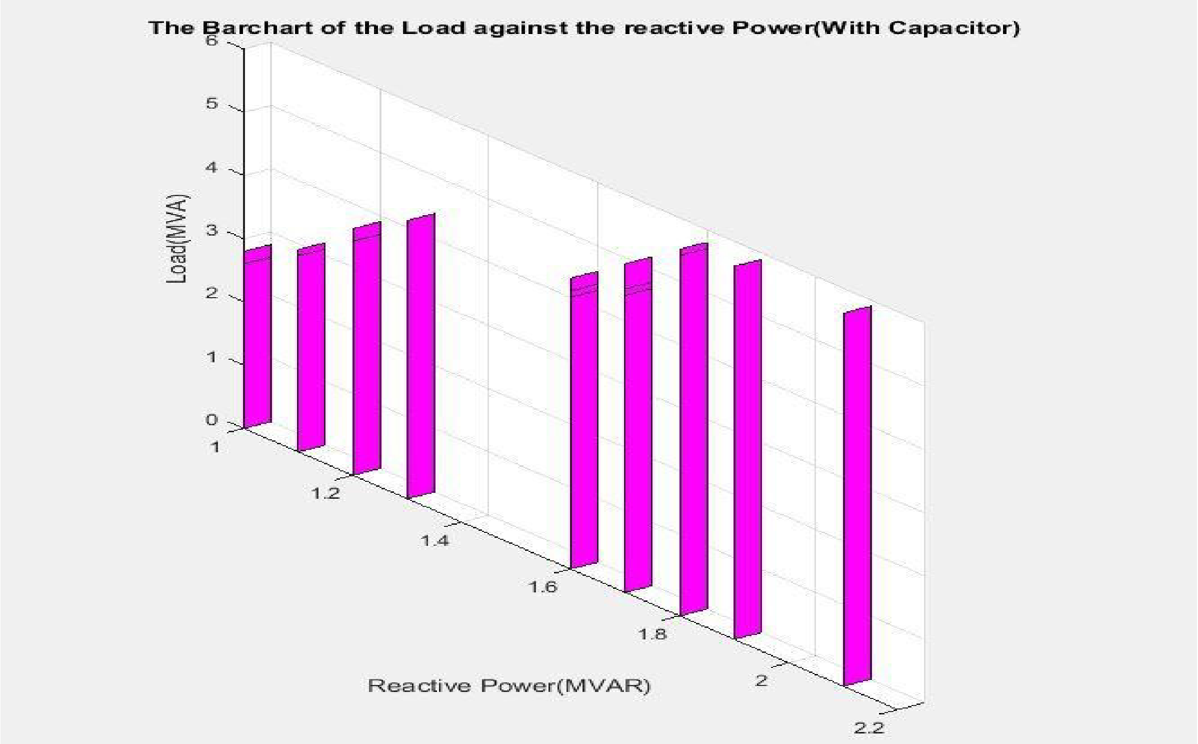

Figure 16: Bar Chart of Load against Reactive Power with Capacitor

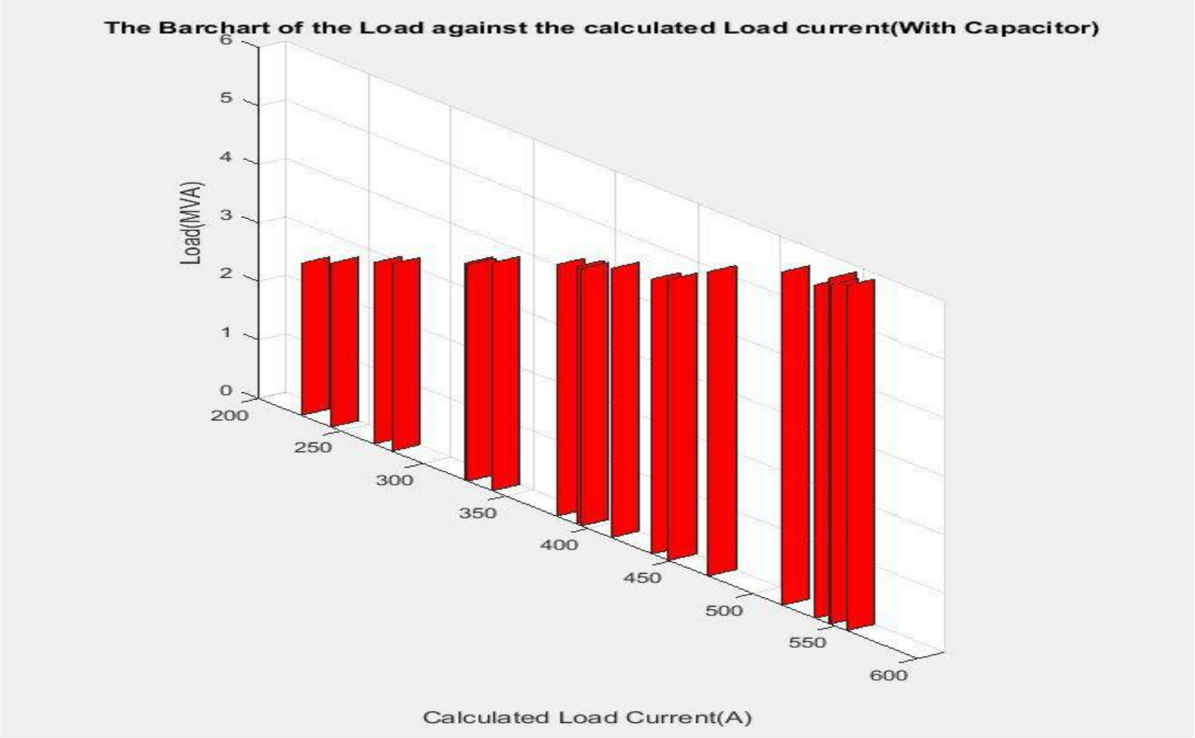

Figure 17: Bar Chart of Load against Calculated Load Current with Capacitor

3.3 Comparison between Simulated Results with and without Capacitor

Figure 18 showed the plot of reactive power with and without capacitor respectively. It was observed that the effects of compensation on the power system were reduction in the reactive power. From the results obtained, it can be depicted that capacitor reduced the load (MVA demand) of the installation, load current, reactive power (MVAR demand). The average MVA loading on the transformer released by 16 % as it was 5.1 MVA before compensation and became 4.3 MVA after compensation. The average power losses on the system reduced by 20 % as the average current drawn was 489 A before compensation and became 392 A after compensation. The capacitor compensated 52 % of the consumed reactive power as the average reactive power was 3.1 MVAR before compensation and became 1.5 MVAR after compensation. The power factor improved by 19 % as it was 0.8 before compensation and became 0.95 after compensation.

It can be deduced from the comparison between simulated results with and without capacitor that the reactive power decreased between the first and second, sixth and seventh, thirteenth and fourteenth, sixteenth and eighteenth as well as twentieth and twenty-fourth hours of the day due to decrease in load demand on the distribution system. However, the reactive power was constant at some hours of the day because of constant in load demand on the distribution system at those hours. Increase in load demand on the distribution system resulted in increase in reactive power during certain hours of the day. In a nutshell, variation in load demand on the distribution system resulted in variation in the reactive power.

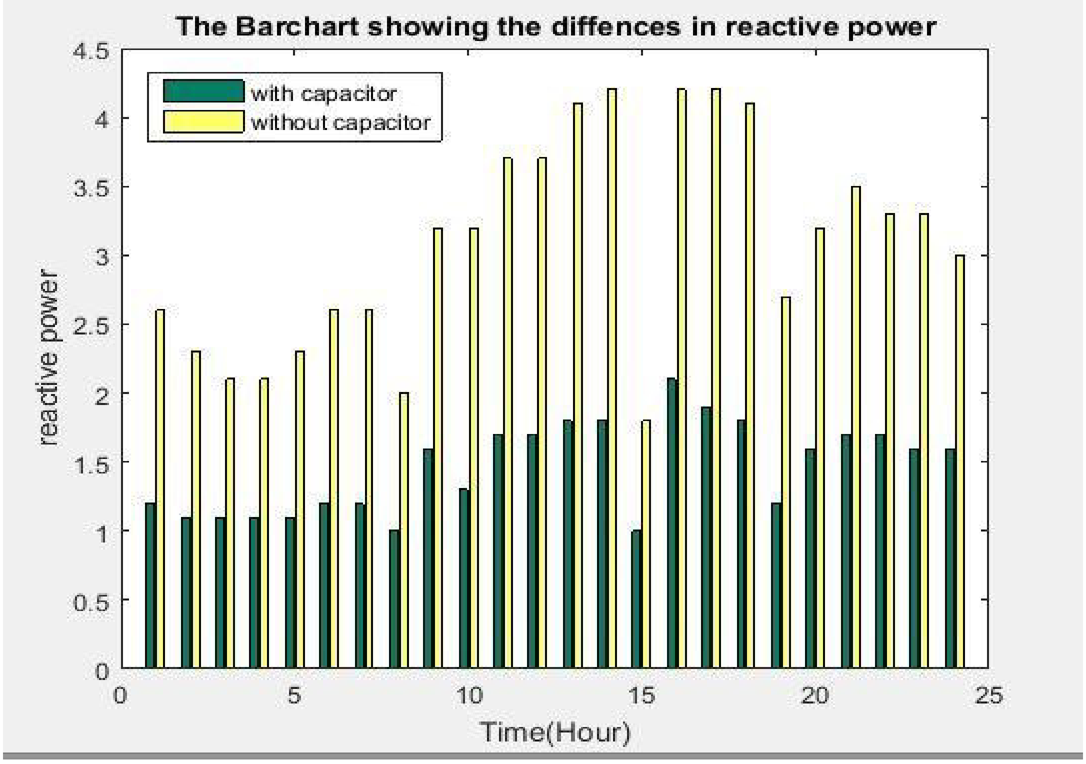

Figure 18: Bar Chart of Reactive Power Profile with and without Capacitor

4. Conclusion

This research paper has considered the application of capacitor switching to control reactive power on primary feeder of Monatan 11 kV distribution injection substation of Ibadan Electricity Distribution Company (IBEDC) Plc. Capacitor Switching Compensation (CSC) was incorporated into the network using KCL algorithm to form Capacitor Switching Compensation Model (CSCM) in order to improve the reactive power of the network and simulation was carried out with and without capacitor switching using MATLAB R2015a application software. The results revealed that the reactive power reduced by 52 % with the application of the Capacitor Switching compared to result without Capacitor Switching incorporated in the network. Consequently, installation of shunt capacitor bank and simulations carried out on Monatan–11 kV Feeder confirmed that Capacitor Switching reduced reactive power consumed, and current drawn thereby reducing the power loss in the network.

Based on the results obtained in this research paper, it is therefore recommended that capacitor of correct size and at correct location should be used for future work in order to regulate the reactive power in distribution system. In addition, conventional mechanical switch capacitor should not be used due to problem of wear and tear; as well as for switch to on and off at the precise time.

5. References

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