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Reactive Power Mitigation and Power Factor Correction in Power Transmission Networks Using Fixed Capacitor Bank

Akeem Babatunde Akinwola, Bassam Abdulrahman Maigel, Fahd Alturki, Karis John, Ezekiel Nnamere Aneke

***Abstract:** Improvement of the power factor and mitigation of reactive power for nonlinear loads is the aim of this article. Power factor plays a significant role in the efficiency of the Electrical power network: a 14-bus 330kV transmission network implemented in the ETAP 19.0 Simulation Environment. A 16MVar capacitor bank was used to inject voltage into the system at bus 6, which had the lowest voltage. The placement of the capacitor bank improved the voltage profile from 94.91% to 95.41% (0.5%). The reactive power component decreased from 100 MVar to 55 MVar. This result enhances the system voltage profile and mitigates the effect of reactive power caused by a lagging power factor.*

***Keywords:** ETAP, PCN, FACTS*

Nomenclature:
TCSC: Thyristor-Controlled Series Capacitor
TCR: Thyristor-Controlled Reactor
FACTS: Flexible AC Transmission Systems
GCSC: Gate-Commutated Series Capacitor
STATCOM: Static Synchronous Compensator

I. INTRODUCTION

The power network of Nigeria consists of a generating station located near fuel sources, a transmission station for interconnecting the generated power, and a load centre that serves as the sink for the generated power. The Nigerian National Grid comprises 29 generating stations, comprising 3 hydrogen and 26 thermal plants, with a total installed generating capacity of 13,063MW.

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The thermal stations are mainly located in the southern part of the country, at Afam, Okpai, Delta, Egbin, and Sapele. The hydroelectric power stations are in the country's middle belt at Kainji, Jebba, and Shiroro. The transmission network comprises 5,395 km of 330kV lines and 6,889 km of 132kV lines, with an installed capacity of 13,063MW [1].

Electrical power demand increases daily due to population growth and technological advancement. Power is mainly generated from fossil fuels, which are limited in nature [2]. Lagging power factor is caused by inductive loads connected to the system. A poor power factor draws more power from the source, making the system less efficient [3]. Several compensation methods have been used for controlling power in transmission lines. Fixed series capacitors were the first technology used to inject reactive power into power lines and reduce load. Power

Electronics-based technologies, commonly known as Flexible AC Transmission Systems (FACTS) controllers, were developed. These include Thyristor-controlled series capacitor (TCSC), Thyristor-controlled reactor (TCR), Gate-commutated series capacitor (GCSC), and Static synchronous compensator (STATCOM).

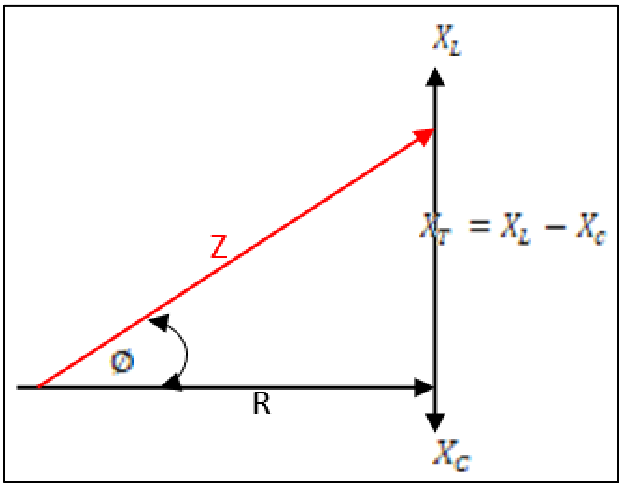
In the current dispensation, the industrial revolution has led to the emergence of automation; attaining the maximum capability of the machines in use has become vital. The efficiency of a given machine is the ratio of its output to the power input. The output power of a machine is less than its input power due to internal losses. Power factor is the ratio of the real current or voltage received by a load to the root mean square (rms) value of the current or voltage that was supposed to be acquired by the same load. The difference in power is due to reactive power in the circuit, which is dissipated as heat [4]. Improving the power factor means reducing the phase difference between voltage and current. Inductive loads require some reactive power to function [5]. To enhance power capability, the power factor needs to be increased to 1. This is achieved using fixed capacitor banks. The ability of power utilities to provide a stable power flow within the specified voltage and frequency range is a critical aspect of power system operation. In an electrical power system with a high reactive load, a power factor closer to one is a strong predictor of overall power quality. Poor factor leads to power losses and higher utility rates. A power factor correction unit improves the power factor of a system and reduces maximum demand [6]. The development of a comprehensive long-term planning strategy in the context of reliability and efficiency improvements in electrical power systems, such as

FACTS devices, enables the transition towards a more innovative transmission network by ensuring stable operation. The integration of compensation devices on each transmission network determines a proper and efficient long-term solution. It improves the voltage profile and reduces power losses [7]. A good-sized centralised reactive power compensation system will meet the power system's requirements. The goals of reactive power compensation for power network systems under different load conditions are best achieved by injecting reactive power into the system. Capacitor banks have satisfactory cost benefits and are widely used for reactive power compensation [8]. The optimal location of shunt capacitors determined using loss sensitivity factors results in a reduction in active power losses [9]. Power flow analysis and its implementation in AC transmission networks have become indispensable for power system planning and operation. A load flow study is a numerical analysis of the flow of electric power in an interconnected transmission system [10]. Mathematically, the power flow problem involves solving a system of nonlinear algebraic equations through an iterative process. In this article, the Newton-Raphson iterative load-flow method was used to analyse the steady-state characteristics of the power network simulated in the ETAP Environment.

II. POWER FACTOR CORRECTION

A. Inductive Loads

Inductive loads require a significant amount of reactive power to operate. Consequently, this reduces the system's power factor.



[Fig.1: Impedance Triangle]

$$Z^2 = R^2 + (X_L - X_C)^2 \quad \ldots \quad (1)$$

Capacitive and inductive reactance have a phase difference of 180 degrees. To compensate for the reactance caused by the inductive component, capacitors need to be added to the circuit.

Given that

$$Cos\varphi = \frac{P}{S} \quad \ldots \quad (2)$$

Where P is the Real Power, and S is the apparent power, For a unity power factor,

$$\frac{P}{S} = 1$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \quad \ldots \quad (3)$$

Where X_L is the inductive reactance, and X_C is the capacitive reactance.

$$X_L - X_C = 0 \quad \ldots \quad (4)$$

$$X_L = X_C$$

From Equation (4), to achieve a high-power factor, capacitive reactance is required to compensate for inductive reactance and reduce the system impedance.

$$X_L = \omega L \quad \ldots \quad (5)$$

$$X_C = \frac{1}{\omega C} \quad \ldots \quad (6)$$

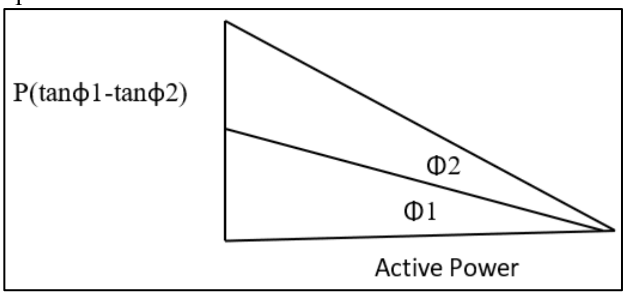
$$\omega_L = \frac{1}{\omega C}$$

$$\omega = \frac{1}{\sqrt{LC}} \quad \ldots \quad (7)$$

$$\omega = 2\pi f$$

Where ω is the angular frequency, L is inductance, C is capacitance, and f is the frequency of the sinusoidal wave of voltage and current provided to the loads.

The amount of reactive power required to inject into the transmission power network to achieve the desired power-factor improvement is determined by the size of the capacitor.



[Fig.2: Power Triangle [6]]

$Q=p\ (\tan\varphi_1 - \tan\varphi_2)$
$Q=2V^2\prod fC$

III. LOAD FLOW STUDY

A load flow study in a power system is primarily known as a steady-state solution of the power system network. This involves preparing the power system modelled as an electric network and solving it to determine steady-state power flows and voltages at various buses. Direct analysis of the circuit is not feasible, as loads are typically specified in terms of complex power rather than impedance, and generators behave more like power sources than voltage sources.

The load flow study provides crucial information, including the magnitudes and phase angles of the voltage at load buses, reactive power flow on transmission lines,

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and power at the reference bus, among other specified variables. This information is vital for continuously monitoring the system's current state and evaluating the effectiveness of alternative plans.

In load flow analysis, voltages at various buses and power flow into the transmission system are considered. are the points of interest. There are several methods employed for load flow analysis, such as the Newton-Raphson, Fast Decoupled Method, and Gauss-Seidel iterative methods. In this article, the Newton-Raphson iterative method is used.

Since we know that

$$I_{bus} = V_{bus}[Y_{bus}] \quad \ldots \quad (8)$$

for an n-bus system, I_{bus} is an nx1 vector with general entry $\boldsymbol{I_i}$. V_{bus} is an nx1 vector with V_i as a general entry, $[Y_{bus}]$ is an nxn matrix with entries Y_{ii} and Y_{ik}. The current entering the ith bus of an 'n' bus system is given by

$$\mathbf{I = Y_{11}V_1 + Y_{12}V_2 + \cdots + Y_{ii}V_{i\ldots\ldots}V_{in}V_n} \quad \ldots \quad (9)$$

$$\sum_{K=1}^{N} \boldsymbol{Y_{ik}\,V_k} = \sum_{K=1}^{N} [\boldsymbol{Y_{ik}\,V_k}] < (\boldsymbol{\delta_k + \theta_{ik}})$$

$$\boldsymbol{Y_{ii} = |V_k| < \delta_k \text{ and } Y_{ik} = |Y_{ik}| < \theta_{ik}} \quad \ldots \quad (10)$$

The complex power injected into the ith bus is

$$S_i = P_i jQ_i = V_i I_i \quad \ldots \quad (11)$$

But the power-flow computation is handled more conveniently by using I_i rather than I^*. Taking the complex conjugate of equation (11)

$$S_i = P_i - jQ_i = V_i^* I_i^* \quad \ldots \quad (12)$$

$$S_i = P_i - jQ_i = V_i^* \sum_{K=1}^{N} Y_{ik}V_k\Big) \quad \ldots \quad (13)$$

$$V_i = |V_i| < \delta_i$$
$$V_i^* = |V_i| < -\delta_i$$
$$Y_{ik} = |Y_{ik}| < \theta_{ik}$$

We have,

$$P_i - jQ_i = |V_i| \sum_{K=1}^{N} |Y_{ik}V_K| < (\theta_{ik} + \delta_k - \delta_i) \quad \ldots \quad (14)$$

Equating real and imaginary parts of equation (14)

$$P_i = |V_i| \sum_{K=1}^{N} |Y_{ik}V_K| \cos(\theta_{ik} + \delta_k - \delta_i) \quad \ldots \quad (15)$$

$$Q_i = -|V_i| \textstyle\sum_{K=1}^{N} |Y_{ik}\,V_K| \sin(\theta_{ik} + \delta_k - \delta_i) \quad \ldots \quad (16)$$

These equations (i.e. Eqn. 15 & 16) are known as static or balanced equations of real and reactive powers of bus (i). They are non-linear and therefore only a numerical solution is possible. For each of the n-bus systems, we have two such equations, giving a total of 2 n equations.

IV. NEWTON-RAPHSON METHOD (NR)

For an N-bus power system, there will be n equations for real power injection Pi and n equations for reactive power injection Qi. The number of equations to be solved depends on the given conditions. If the total number of buses is N and the number of generator buses is M, then the number of equations to be solved will be the number of known Pi's and the number of known Qi's.

In the given conditions, the number of known Pi's is $n - 1$, and the number of known Qi's is $(n - m)$. Therefore, the total number of simultaneous equations will be $2 \times (n - m - 1)$, and the number of unknown quantities will also be $2\ \mathrm{x}(\mathrm{n} - \mathrm{m} - 1)$. The unknowns to be calculated are the power angles (δ) at all buses except the slack bus $(\mathrm{N} - 1)$ and the bus voltages (V) at the load buses (n-m).

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad \ldots \quad (17)$$

Where;

$$\Delta P = P_i(\text{ specified }) - P_i(\text{ calculated})\ \Delta Q = Q_i(\text{ specified }) - Q_i(\text{ cal }) \quad \ldots \quad (18)$$

Terms of absolute power will be calculated for all buses except the slack bus, and reactive power terms will be calculated for all load buses.

Where;

$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$ is the mismatch power vector

$\begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix}$ is the correction vector

$$J = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix} \quad \ldots \quad (19)$$

equation (19) is the Jacobian matrix

In the application of the NR method, we first have to bring the equations to be solved to the form $f(x_1, x_2, \ldots, x_n) = 0$, where $x_1, x_2, \ldots, x_n$ are the unknown variables to be determined. Let us assume that the power system has n_1PV buses and n_2PQ buses. In polar coordinates, the unknown variables to be determined are:

i. δ_i is the angle of the complex bus voltage at bus i, at all the PV and PQ buses. This gives us $n_1 + n_2$ Unknown variables to be determined.

ii. $|V_i|$, is the voltage magnitude at bus i for all PQ buses. This gives us n_2 Unknown variables to be determined. Therefore, the total number of unknown variables to be computed is: $n_1 + 2n_2$, for which we need $n_1 + 2n_2$ Consistent equations to be solved. The equations are given by,

$$\Delta P_i = P_{isp} - P_{ical} = 0 \quad \ldots \quad (20)$$
$$\Delta Q_i = Q_{isp} - Q_{ical} = 0 \quad \ldots \quad (21)$$

Where;

$P_{i,sp}$ = Specified active power at bus i

$Q_{i,sp}$ = Specified reactive power at bus i

$P_{i,\,cal}$ = Calculated value of active power using voltage estimates.

$Q_{i,cal}$ = Calculated value of

reactive power using voltage estimates
ΔP = Active power residue
ΔQ = Reactive power residue

The real power is specified at all the PV and PQ buses. Hence, Equation (20) is to be solved at all PV and PQ buses, leading to $n_1 + n_2$ equations. Similarly, the reactive power is

specified at all the PQ buses. Hence, Equation (21) is to be solved at all PQ buses leading to n_2 equations.

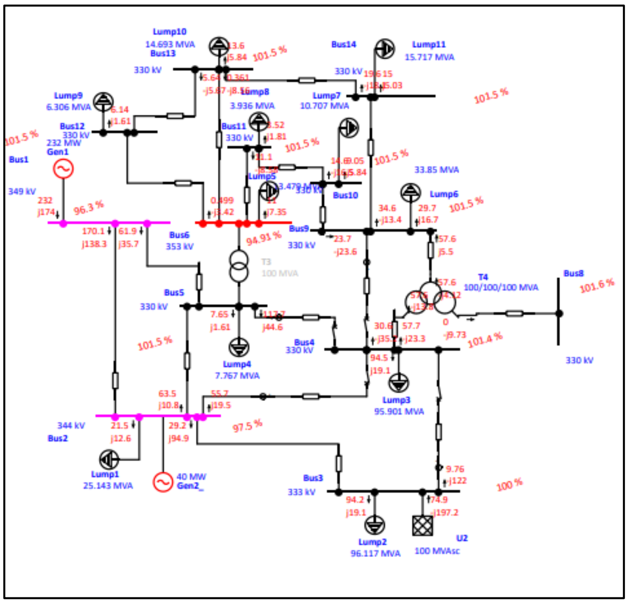
We thus have $n_1 + 2n_2$ equations to be solved for $n_1 + 2n_2$ unknowns. Equations (20) and (21) are of the form F(x) = 0 .

Hence,

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad \dots \quad (22)$$

Where J_{11},J_{12},J_{21},J_{22} are the negated partial derivatives of ΔP and ΔQ with respect to the corresponding δ and $|V|$.

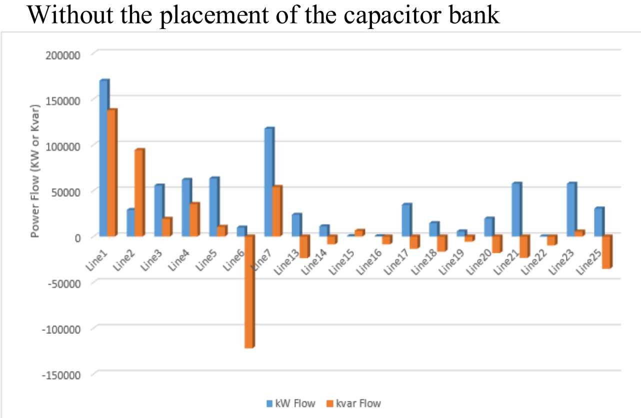
V. RESULTS



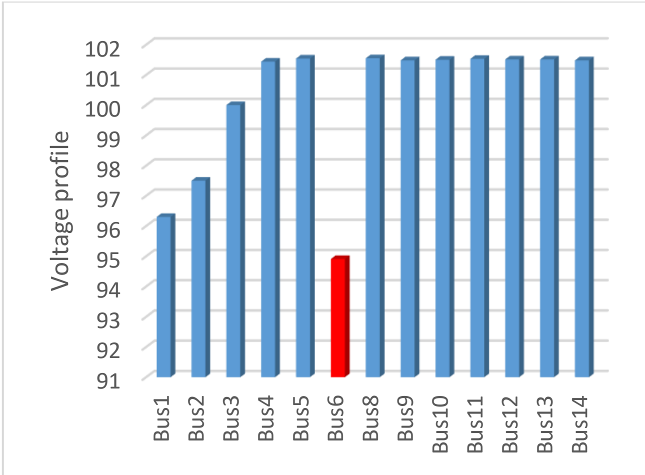
[Fig.2: Load Flow Result Without Capacitor on 14 Bus Transmission Network]

The load flow result shows a steep voltage at bus 6 due to the inductive components of the load.

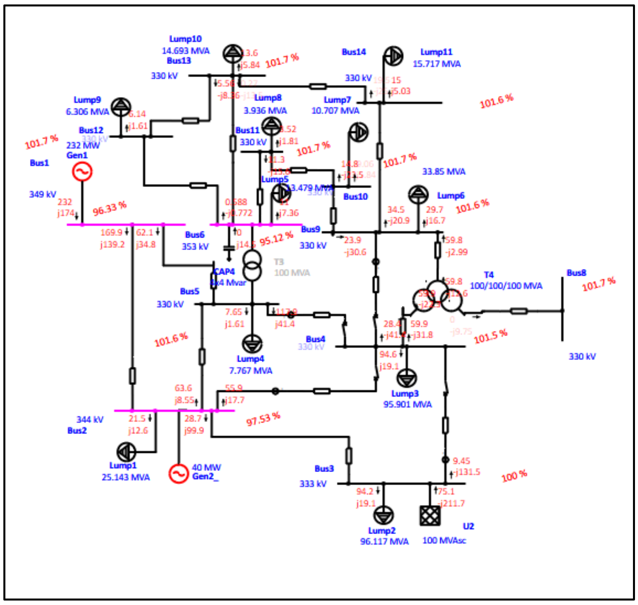
Without the placement of the capacitor bank



[Fig.3: Power Flow Profile Result Without Capacitor on 14 Bus Transmission Network]

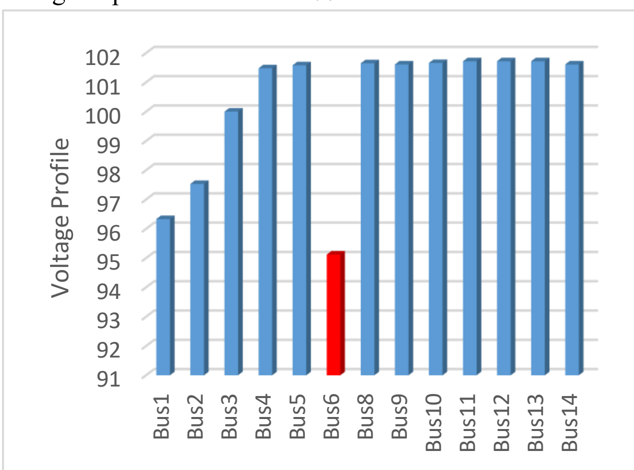


[Fig.4: Voltage Profile After Load Flow Analysis]



[Fig.5: Load Flow Result with Capacitor on 14 Bus Transmission Network]

A 16 MVAr capacitor bank was connected at bus 6, and the voltage improved to about 50%.



[Fig.6: Voltage Profile After Load Flow Analysis]

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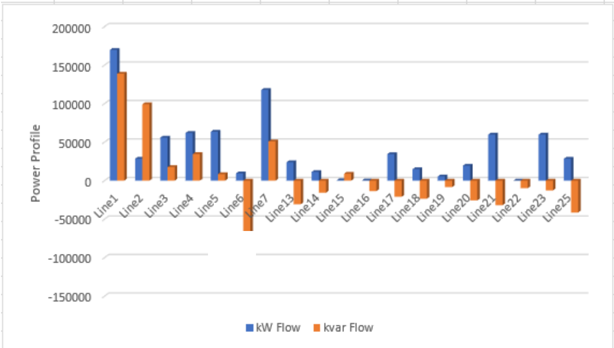

[Fig.7: Power Flow Profile Result with Capacitor Bank on 14 Bus Transmission Network]

The connection of the 16MVar Capacitor bank at bus 6 reduced reactive power by 45%, from 100 MVAr to 55 MVAr, while improving power factor.

VI. CONCLUSION AND RECOMMENDATION

The presence of a capacitor bank connected to the 14-bus power transmission network reduced reactive power in the system and improved real power flow. There has been an improvement in the power factor of the 14-bus transmission network.

This article mitigated the effects of reactive power in a 14-bus, 330kV power transmission network by connecting a 16 MVar capacitor bank at bus 6, the most sensitive bus with a low-voltage profile and a high leading power factor.

We recommend using FACT devices to achieve faster and more reliable power-factor improvement and reactive-power compensation in a power transmission network.

DECLARATION STATEMENT

As the article's author, I must verify the accuracy of the following information after aggregating input from all authors.

Some of the references cited are outdated, noted explicitly as [2], [3] and [8]. However, these works remain significant for the current study, as they are pioneering in their fields.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been funded by any organizations or agencies. This independence ensures that the research is conducted objectively and without external influence.
- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate with supporting documentation.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

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