# Load Flow Evaluation of 11kV Distribution Network for Enhanced Power Supply Using Static Compensator

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***Abstract***

*This study conducted load flow analysis of 11kV distribution network of Rumuomoi, Rivers state, Nigeria, with aim of enhancing power supply by the network through reactive power compensation. The simulation is carried out using Newton Raphson method embedded in ETAP software. It is achieved by running a load flow of the existing 11KV distribution network, determining the losses from the load flow. Minimizing the determined losses in 11/0.415KV power distribution network by incorporating a PSO optimized STATCOM in the bus with maximum stability index in the network. Then, validating the percentage of loss reduction, and enhanced voltage profile in the distribution network with and without the inclusion of an optimized STATCOM. The result obtained shows that out of the twelve (12) load buses in the existing network ,three(3) were critically loaded, one(1) was marginally loaded and the remaining eight(8) buses were in good loading conditions. The total real and reactive power losses is 106.024kW and 161.58kVar respectively. But when an optimized STATCOM (320MVar) placed at bus (6) is penetrated into the network, the result shows that all the buses in the network are all in normal operating conditions. The total real and reactive power losses is 19.78KW and 30.98KVar respectively. There is 81% reduction in both real and reactive power losses .In addition when STATCOM is penetrated, all the transformers maintain good loading conditions and voltage profile of all the buses fall within +5% variation as stipulated by IEEE.*

***Keywords***: *Newton Raphson, ETAP, STATCOM, Real Power, Reactive Power, Voltage Profile, PSO, IEEE*

## I. INTRODUCTION

Distribution systems hold a very significant position in the power system since it is the main point of link between bulk power and consumers [1]. Effective planning of radial distribution network is required to meet the present growing domestic, industrial and commercial load day by day. Power flow analysis is an important tool used by engineers to ensure stable operation of the power system, it is also used in load forecasting, scheduling, planning, control and operations of existing electric power systems as well as planning for future expansion[2][3]

Potential problems in the distribution networks like unexpected spikes, harmonic interference, excessive voltage deviations and acceptable power losses that may not be seen during a visual inspection can only be determined by carrying out load flow study [4]. It is necessary to conduct load flow study in order to guarantee that electric power systems are safe and efficient.

Load flow study or power flow study is an essential tool describing numerical analysis amplified notation such as a single line diagram and per unit system and focuses on various power system quantities (Voltage magnitude, Voltage angles, Real power and Reactive power). With increase in the load demand, more inductive loads are engaged to the distribution network by consumers, the voltage at the load points reduces, which further increases the system loss and the system becomes less efficient, this situation is indicated by low power factor at the load point [5[[6] The general approach to mitigate this problem is through reactive power compensation. So, for this reason, a better approach to improve the power factor is needed, here the penetration of FACTS device come to play, that will match the required reactive power needed by loads to minimize power loss in the distribution system. This reason motivates this research, to evaluate the load flow of a typical distribution network and enhanced its power supply through the penetration of sizeable Static Compensator (STATCOM).

## II. Statement of the Problem

The practice of load shedding by the utility company in Nigeria as a result of inadequate and unstable power supply has been a huge burden on all categories of electricity consumers (domestic, commercial and industrial). The distribution network of Rumuomoi, Port-Harcourt has been experiencing unreliable power supply coupled with low voltage profile and high-power losses. This problem is leading to damaging of equipment connected to the system, partial shutdown of businesses in the area that require reliable power supply, and loss of revenue by the utility company. In order to mitigate the problem, performing a load flow study and adequate reactive power compensation will be required so as to assess and restore a stable and efficient power supply in the study area. This research will propose power supply enhancement of the distribution system with the penetration of FACTs device (STATCOM) for reactive power compensation.

## III. LITERATURE REVIEW

According to [7], he proposed a study on the development of an improved 11kV electrical power distribution network for the former Port Harcourt Township (Borokiri), using Rapid decoupled flow approach. During the investigation, it was shown that the study case area network was characterized by the issue of low voltage profile, frequent power outages when all the substation were examined. To overcome this challenges, transformer load tap changing (LTC) were utilized on 2×15MVA transformers at the Borokiri injection substation, as well as by boosting the power factor by penetrating shunt capacitor in the weak buses of the network, both of which were accomplished. In his opinion both approaches yield good outcome.

According to [8], in their proposed study, assessed the electrical load on the 33kV Igwuruta distribution network using the Electrical Transient Analysis program. It was discovered that the existing distribution transformers were overloaded which caused low voltage performance throughout the network. A perfect capacitor banks with a capacity of 4800Kvar was introduced into the network, the entire system network was adjusted with an improvement in the voltage profile that was within the regulation range of 95% to 100%.

According to [9], they carried out s study on the enhancement of voltage stability of the Nigerian 330kV transmission network using ANN controller. They modelled and by run load flow of the network, where the buses that fall short of the statutory minimum voltage stability range of 0.95 through 1.0 were identified. By designing a conventional SIMULINK model for the voltage stability enhancement using ANN controller. ANN controller was incorporated in the system which resulted to an increase in the system per unit volts to 1.047.

According to [10], they proposed a study on optimal location and compensation of a distribution system using DSTATCOM, modeling a hybrid Whale with Grey Wolf Optimization (WG), for determining its optimal placing and sizing. Comparing the proposed WG algorithm performance with other conventional methods such as GA, ABC, PSO, GWO, and WOA in terms of convergence analysis, cost analysis, and total loss, it was concluded that the effectiveness of the proposed power quality model is significant.

According to [11], they presented a study on optimal siting and sizing of Distribution Static Compensator(D-STATCOM) on a radial distribution network using Particle Swarm Optimization(PSO) technique, with aim of achieving the power loss reduction and maximize voltage profile in the network Voltage stability index was used to identify optimal placement for the D-STATCOM, while PSO was employed to deduce the size of D-STATCOM for the weak buses. The validity of the method is tested in the IEEE 12 and 34 Bus radial distribution system at Checkanurani substation rating of 110/11 KV in Madurai. Load flow analysis was performed and the bus voltage and power loss was obtained in MATLAB. The results obtained were compared without and with D-STATCOM. By the optimal placement and sizing of D-STATCOM the voltage profile improved and the power loss reductions are obtained in the Checkanurani substation located in Madurai, Tamilnadu.

## IV. METHODOLOGY

The study case distribution system (11kV Rumuomoi network) was modelled and simulated using embedded Newton Raphson technique in Electrical Transient Analyzer Program environment, for load flow studies. The system losses and voltage profiles at each bus in the network were recorded. Then, the system was compensated with the penetration of reactive power through STATCOM. Before doing this, algorithm for the Newton-Raphson's method was developed alongside the Voltage Stability Index (VSI) which is used for the optimal placement of the reactive power component (STATCOM) while the Particles Swarm Optimization (PSO) was used for sizing the value of suitable reactive power component. Tables 1 and 2 show the load and line data of the network respectively.

**Table 1: Load Data**

| S/N | Bus Name | Transformer rating (KVA) | Average load current (A) | Rated current of transformer (A) | Percentage loading of transformer (%) | Load apparent power (KVA) | Load active power (KW) |
|---|---|---|---|---|---|---|---|
| 1 | Ohiamini Rd | 500 | 263.33 | 695.60 | 37.86 | 189.30 | 160.91 |
| 2 | Location Rd | 500 | 230.00 | 695.60 | 33.06 | 165.3 | 140.51 |
| 3 | Ideogu Estate | 500 | 354.33 | 695.60 | 50.94 | 254.7 | 216.50 |
| 4 | Omunaka Rd | 300 | 433.67 | 417.36 | 103.91 | 311.72 | 264.97 |
| 5 | Okabie Rd | 300 | 456.00 | 417.36 | 109.26 | 327.78 | 278.61 |
| 6 | Amadi Rd 1 | 300 | 460.00 | 417.36 | 110.22 | 330.66 | 281.06 |
| 7 | Amadi Rd 2 | 500 | 357.33 | 695.60 | 51.37 | 256.85 | 218.32 |
| 8 | Bakery Rd | 500 | 380.00 | 695.60 | 54.63 | 273.15 | 232.17 |
| 9 | Silicon Valley ltd | 500 | 373.33 | 695.60 | 53.67 | 268.35 | 228.10 |
| 10 | PHWC | 500 | 378.67 | 695.60 | 54.01 | 270.00 | 229.53 |
| 11 | Super Geometrics | 300 | 383.67 | 417.36 | 91.93 | 275.78 | 234.41 |

**Source:** Port Harcourt Electricity Distribution Company (PHED)

**Table 2: Line Data**

| Line ID | From Buss | To Bus | Impedance (Z) | Admittance (Y) | Suscep (B) | Distance (km) |
|---|---|---|---|---|---|---|
| 1 – 2 | Ohiamini Rd | Location Rd | 0.015 + j0.057 | 0.0432 – j0.1641 | 0.00164 | 0.32 |
| 2 – 3 | Location Rd | Ideogu Rd | 0.087 + j0.049 | 0.0981 – j0.1800 | 0.00130 | 0.34 |
| 3 – 4 | Ideogu Rd | Omunakwu Rd | 0.026 + j0.028 | 0.1781 – j0.1918 | 0.00192 | 0.33 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 4 – 5 | Omunakwa Rd | Okabie Rd | 0.049 + j0.041 | 0.1200 – j0.1004 | 0.00100 | 0.36 |
| 5 – 6 | Okabie Rd | Amadi Rd 1 | 0.083 + j0.025 | 0.1105 – j0.333 | 0.000333 | 0.35 |
| 6 – 7 | Amadi Rd 1 | Amadi Rd 2 | 0.040 + j0.011 | 0.2824 – j0.0639 | 0.000637 | 0.34 |
| 7 – 8 | Amadi Rd 2 | Bakery Rd | 0.058 + j0.030 | 0.1360 – j0.0704 | 0.000704 | 0.311 |
| 8 – 9 | Bakery Rd | Silicon Valley | 0.027 + j0.059 | 0.0641 – j0.1901 | 0.00140 | 0.362 |
| 9 – 10 | Silicon Valley | PHWC | 0.055 + j 0.047 | 0.1051 – j0.098 | 0.000898 | 0.35 |
| 10 – 11 | PHWC | Super Geometrics | 0.055 + j0.047 | 0.1051 – j0.0598 | 0.000898 | 0.37 |
| 11- 12 | Super Geometrics | Idiegbo Rd | 0.088 + j0.060 | 0.0776 – j0.029 | 0.00529 | 0.30 |

**Source:** Port Harcourt Electricity Distribution Company (PHEDC)

- **Newton Raphson Load Flo Method Used in ETAP**

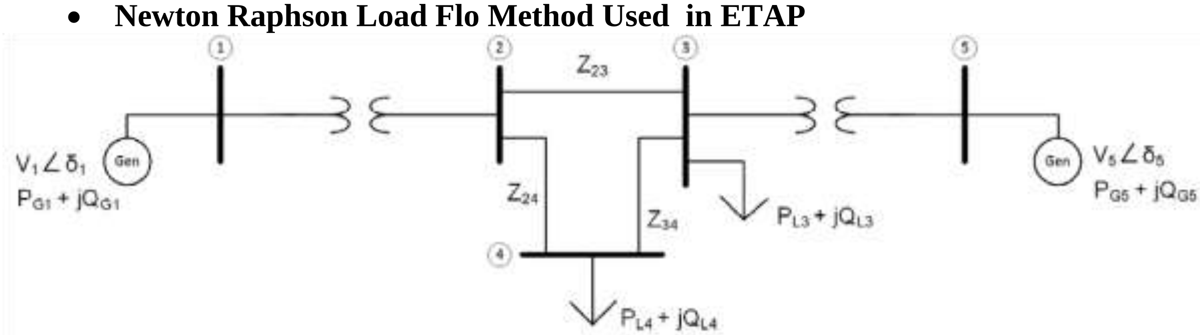


**Figure 1: Single Line Diagram of a Typical Power System.**

The apparent power injected at the *ith* node is

$$S_i = V_i I_i^* = P_i + jQ_i \quad (1.1)$$

$$I_i = \left(\frac{S_i}{V_i}\right)^* = \frac{P_i - jQ_i}{V_i^*} \quad (1.2)$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} = \sum_{k=1}^{n} Y_{ik} V_k \quad (1.3)$$

$$P_i - jQ_i = V_i^* \left(\sum_{k=1}^{n} Y_{ik} V_k\right) \quad (1.4)$$

Let $V_i^* = \mathrm{V_i}\angle - \delta_i, V_k = \mathrm{V_k}\angle\delta_k$ and $Y_{ik} = Y_{\mathrm{ik}}\angle\theta_{ik}$

$$P_i - jQ_i = V_i \ \left(\sum_{k=1}^{n} Y_{ik} V_k \angle\delta_k + \theta_{ik} - \delta_i\right) \quad (1.5)$$

$$P_i - jQ_i = \sum_{k=1}^{n} |Y_{ik}||\mathrm{V_i}||\mathrm{V_k}| \left[\cos(\delta_k + \theta_{ik} - \delta_i) + j\sin(\delta_k + \theta_{ik} - \delta_i)\right] \quad (1.6)$$

Separating the real part from the imaginary part in (1.6)

$$P_i = \sum_{k=1}^{n} |Y_{ik}||\mathrm{V_i}||\mathrm{V_k}| \cos(\delta_k + \theta_{ik} - \delta_i) \quad (1.7)$$

$$Q_i = -\sum_{k=1}^{n} |Y_{ik}||\mathrm{V_i}||\mathrm{V_k}| \sin(\delta_k + \theta_{ik} - \delta_i) \quad (1.8)$$

Where
$Y_{\mathrm{ik}}$= admittance
$P_i$= real power
$Q_i$= reactive power
$\delta_i$= phase angle
Expanding (1.7) and (1.8) in Taylors series neglecting higher order terms we have

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \frac{\Delta P_n^{(k)}}{\Delta Q_2^{(k)}} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \begin{vmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} \end{vmatrix} & \begin{vmatrix} \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \end{vmatrix} \\ \begin{vmatrix} \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} \end{vmatrix} & \begin{vmatrix} \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{vmatrix} \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \frac{\Delta \delta_n^{(k)}}{\Delta \left| V_2^{(k)} \right|} \\ \vdots \\ \Delta \left| V_n^{(k)} \right| \end{bmatrix} \qquad (1.9)$$

With minor changes in real $\Delta P_i^{(k)}$ and reactive power $\Delta Q_i^{(k)}$the Jacobian matrix shows the linearized correlation between tiny changes in voltage angle $\Delta\delta_i^{(k)}$ and magnitude $\Delta\left|V_i^{(k)}\right|$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \qquad (1.10)$$

Where
$J_1, J_2, J_3, J_4$ are the elements of the Jacobian matrix
The diagonal and the off diagonal elements of $J_1$ are

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{k\neq i} |Y_{ik}||V_{\mathrm{i}}||V_{\mathrm{k}}| \sin(\delta_k + \theta_{ik} - \delta_i) \qquad (1.11)$$

$$\frac{\partial P_i}{\partial \delta_k} = -\,|Y_{ik}||V_{\mathrm{i}}||V_{\mathrm{k}}| \sin(\delta_k + \theta_{ik} - \delta_i) \qquad k \neq i \qquad (1.12)$$

Similarly, the diagonal and off diagonal element of $J_2, J_3, J_4$ can be computed

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \qquad (1.13)$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \qquad (1.14)$$

Equations 1.1 to 1.14 are the fundamental power flow equations and its solution is facilitated using the traditional Newton Raphson solution algorithm embedded in ETAP

- **Optimal Placement of STATCOM Using Particle Swarm Optimization**

The study's major aim is to strengthen the system's VSI to prevent voltage instability and to identify and enhance the bus with the lowest stability index in the network. Reduction of losses and maintaining a voltage profile of the distribution system was done by using STATCOM of optimal rating at appropriate location. The objective of the optimal placement and sizing of STATCOM is to minimize the total power loss in the distribution network with voltage profile improvement.

Min f = Min (PT loss**)** **(**1.15**)**

**Constraints:**
The reactive power injected by STATCOM to the system is limited by upper and lower boundary given:

$$Q_{min} \ll STATCOM \ll Q_{max} \tag{1.16}$$

The system voltage in all buses should be within an acceptable limit.

$$\boldsymbol{V_{min}} \ll V_i \ll V_{max} \tag{1.17}$$

$V_i$ is the voltage of ith bus and i bus varies from 1 to number of buses.

- **Voltage Stability Index**

Voltage Stability Indicator is used to see how near the network is to collapse. VSI determines the system's poorest node, which is the most vulnerable to voltage collapse. The voltage stability index is used to determine which circuit is most vulnerable to voltage instability. The expression for Voltage Stability Index is given by:

$$V.S.I = \frac{4ZQ}{V^2X} \tag{1.18}$$

Where,
Z= Impedance
X= Reactance
Q= Reactive power
V= Bus Voltage

## V. RESULTS AND DISCUSSIONS

### Diagrams With and Without STATCOM Injection

Figures 2 and Figure 3 depict the one line simulation diagrams of the study case network without and with PSO optimized STATCOM injection respectively. As shown in Figure 2, the base case, three (3) load buses are critically loaded (Red colour), one(1) is marginally loaded(Purple colour), and while the remaining eight(8) load buses are certified good(Black colour). As shown in Figure 3, with the injection of a single PSO optimized STATCOM of 320MVar at bus 6, all defective load buses were successfully upgraded from critical and marginal loading condition to normal condition (Black colour).

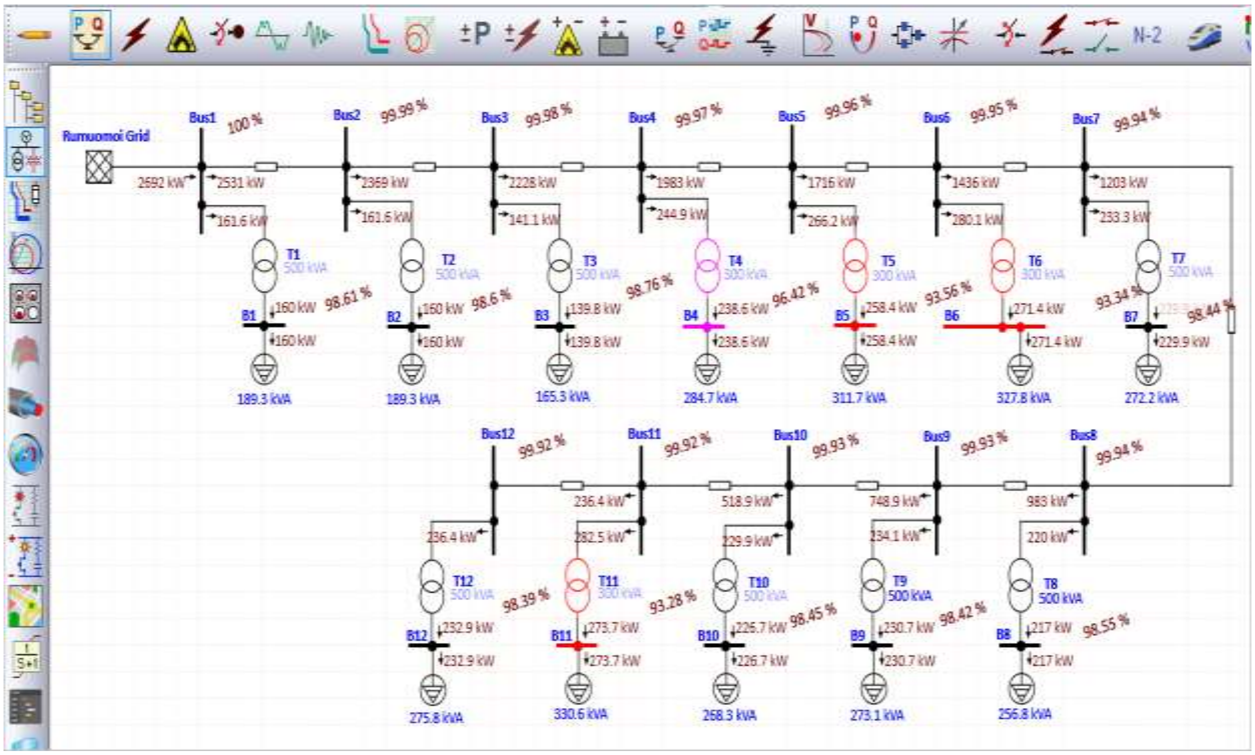


**Figure 2: Base Case Simulation of Rumuomoi 11kV Distribution Network**

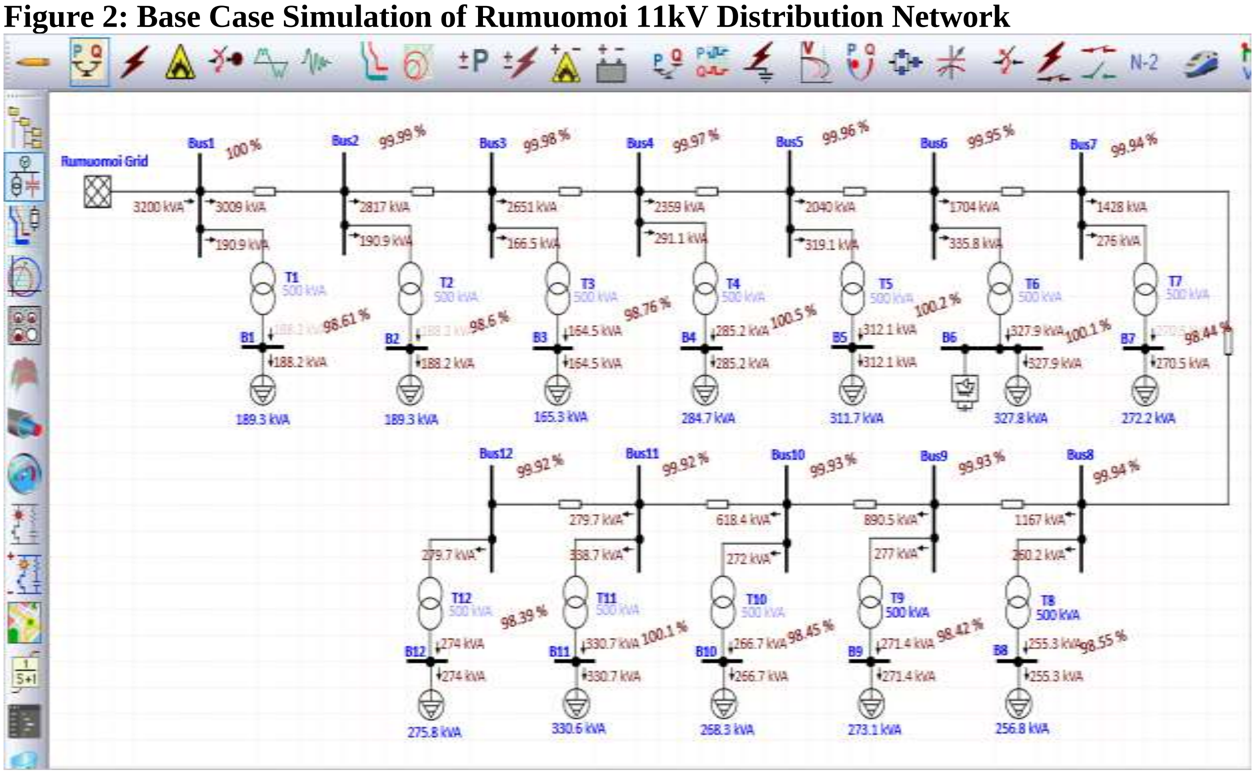

**Figure 3: Improved Case of Rumuomoi 11kV Distribution Network**

- **Discussion of Optimal Sizing and Placement of STATCOM**

Particle Swarm Optimization (PSO) algorithm was deployed to estimate the amount of reactive power needed for voltage profile optimization and power loss minimization, while Voltage stability Index (VSI) was used to determine the location. The maximum stability index was found to be 2.5353 which corresponds to bus 6 for optimal location of STATCOM. From the optimal parameter values, it was revealed that 320MVar is the sixth value (bus 6) in the vector, and it is the bus where STATCOM of 320MVar will be placed for compensation.

- **Bus Voltage Profile With and Without STATCOM Injection**

Figure 4 shows a composite bar chart illustrating the percentage of bus voltage magnitude with and without penetration of PSO optimized STATCOM in the network. Without injection of STATCOM in the network, it was observed that four (4) out of twelve (12) buses are overloaded (3 critically and 1 marginally). The voltage profiles of buses 5, 6 and bus 11 violated the statutory voltage limit variation of $\pm$5% as declared by IEEE. After the injection of optimized STATCOM (320Mvar) into the network, all the buses, including $4{,}5{,}6\ and\ 11$ were upgraded from marginal/ critical position into good loading condition with acceptable voltage deviation limit of ±5% declared by IEEE.

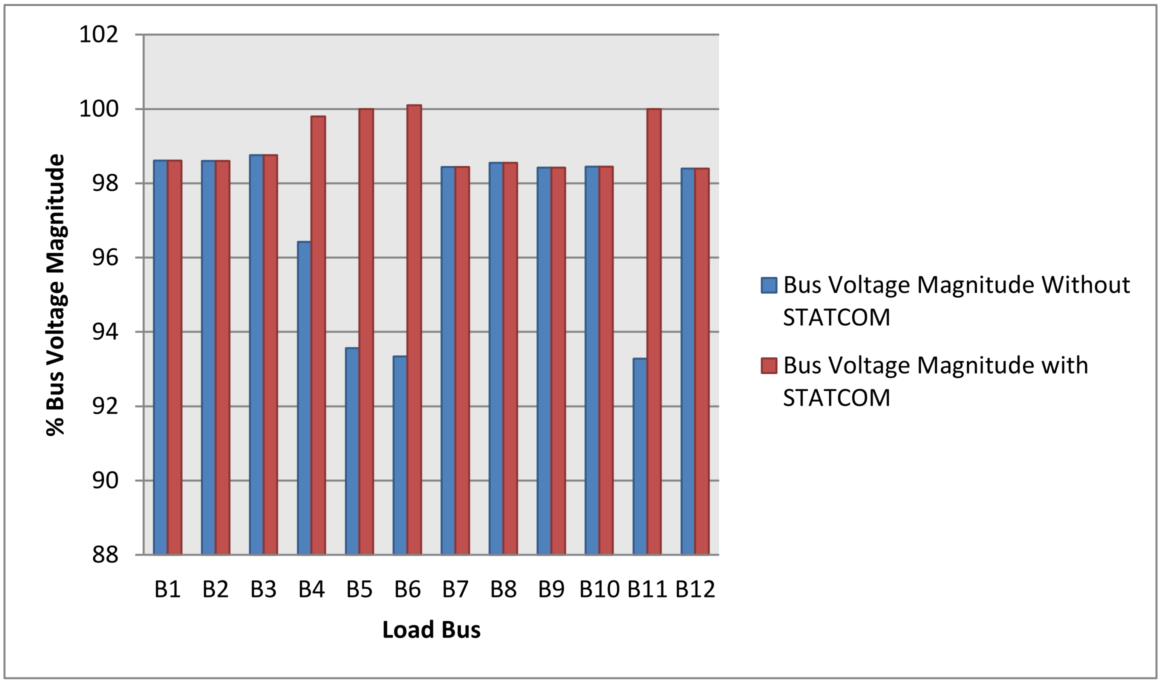


**Figure 4: Composite Bar Chart of Percentage Bus Voltage Magnitude**

- **Real Power Loss With and Without STATCOM Injection**

Figure 5 depicts line graphs illustrating the real power losses in the network with and without STATCOM penetration. With the injection of PSO optimized STATCOM (320Mvar) in the network, there is a significant reduction in real power loss. The total real power loss recorded without STATCOM was 106.02kW, while with STATCOM recorded is 19.78kW.

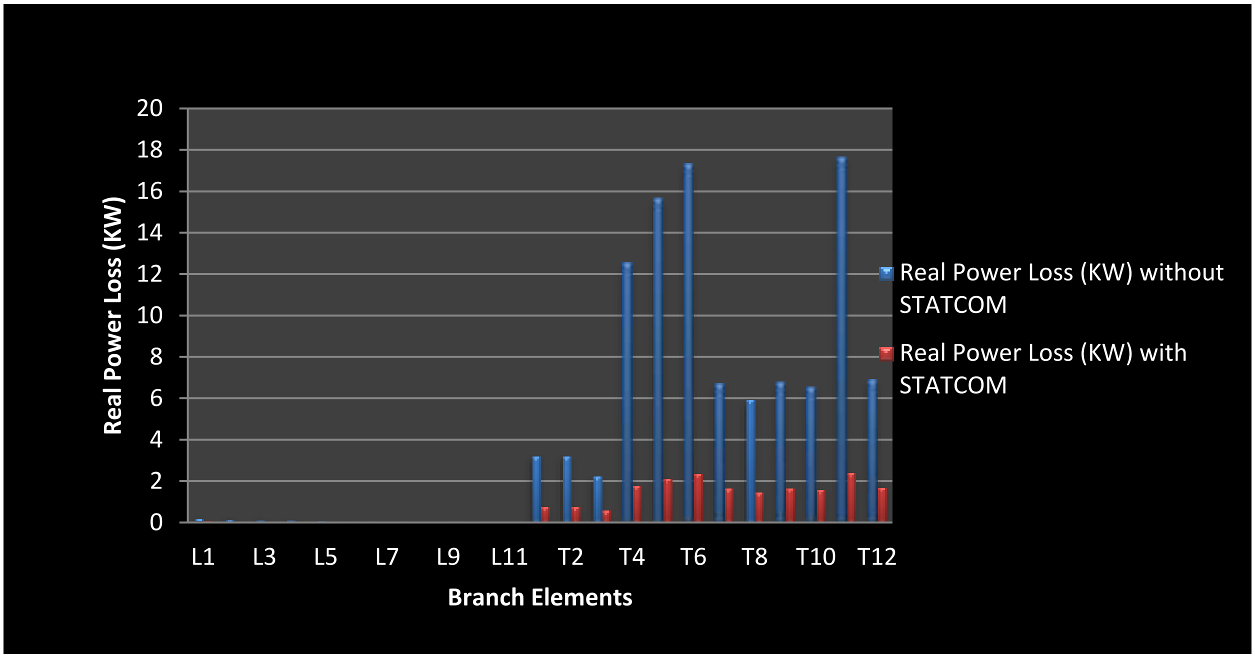


**Figure 5: Line Graph of Real Power Loss**

**Reactive Power Loss With and Without STATCOM Injection**

Figure 6 shows line graphs illustrating the reactive power losses in the network with and without STATCOM penetration. With the injection of PSO optimized STATCOM (320Mvar) in the network, there is an appreciable reduction in reactive power loss. The total reactive power loss with and without STATCOM is 30.98kVar and 161.58kVar respectively.

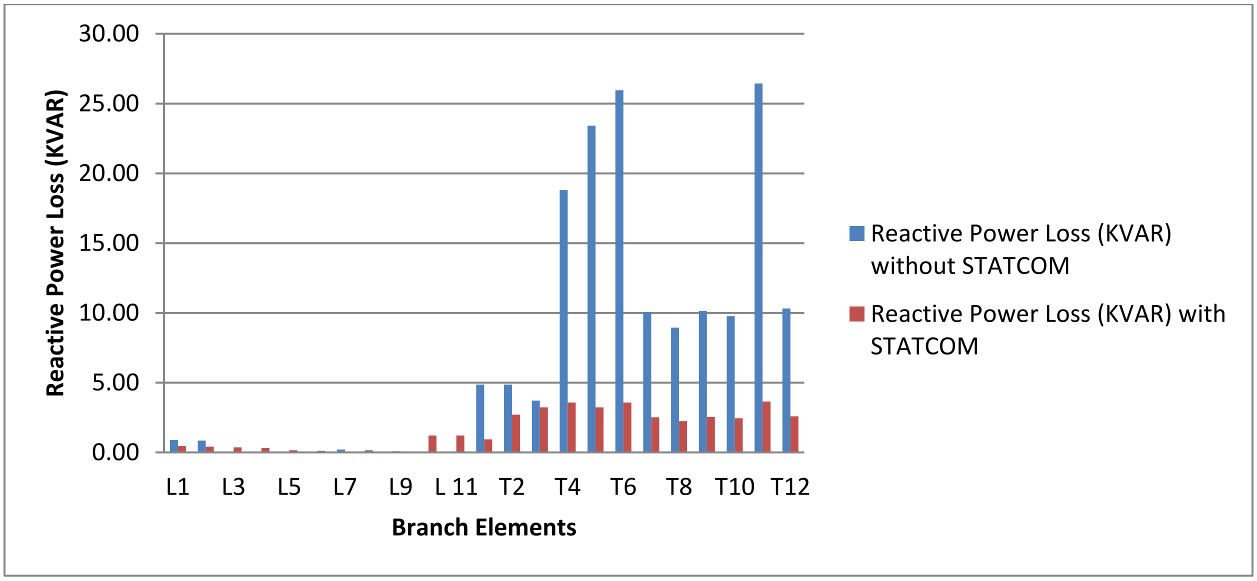


Figure 6: Line Graph of Reactive Power Loss.

**Transformer Loading With and Without STACOM Injection**

Figure 7, shows a composite bar chart illustrating the percentage loading of over stressed transformers with and without penetration of PSO optimized STATCOM in the network. There is a huge reduction in percentage loading of over stressed transformers STATCOM penetration. The percentage loadings of four over stressed transformers T4, T5, T6, T11 which are 97,105.6, 111.2, and112.2 now reduced to 58.2, 63.8, 67.2 and 67.7 respectively after compensation.

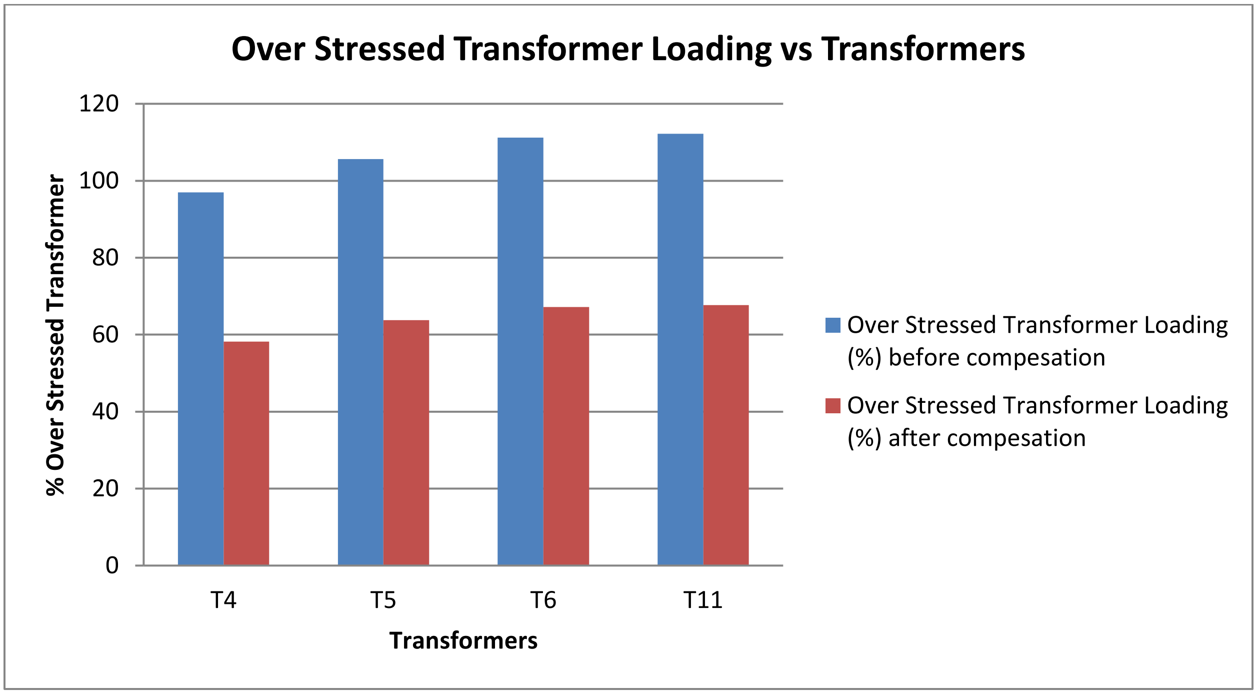


**Figure 7: Composite Bar Chart of Percentage Loading of Overstressed Transformers**

## VI. Conclusion

Unstable power supply in radial distribution network associated with large voltage deviation and huge power losses can be minimized with adequate reactive power compensation to achieve stable operating condition of the power system. This study carried out load flow evaluation of 11kV distribution network with adequate reactive power compensation for enhanced power supply, through the injection of STATCOM. Load flow study of the network was performed using Electrical Transient Analyzer Program (ETAP) simulation tool to ascertain the existing condition of the network. In order to enhance the performance of the system, a single STATCOM (320Mvar) was injected into the network using VSI and PSO for its placement and sizing. The results obtained shows that when a PSO optimized STATCOM (320Mvar) was injected into the network, the total real power loss reduced from 106.2kW to 19.78kW, and the total reactive power loss reduced from 161.58kVar to 30.98kVar. This means that at the instance of injecting STATCOM (320Mvar) into the network, the real and reactive power losses reduced by 81% and 80% respectively, and all the bus voltage falls within IEEE voltage variation of ±5% benchmark. Also, all the transformers returned to healthy loading.

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