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Optimal Capacitor Placement in 11kv Distribution Network for Improved Power Quality

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ABSTRACT: Power Loss and poor voltage profile are the consequences of a distribution system operating at low lagging power factor. The inductive nature of most distribution system and loads are the factors that contribute to low lagging power factor of a power system, which can be improved by injecting leading reactive power through capacitor bank to the power system, to partly or completely neutralize the lagging reactive power. However, to get effective results, capacitor has to be optimally placed in the power system. This research presents an effective way to improve the power quality of a network using Electrical Transient Analyzer Program, with Rivers State University 11kv distribution network as a case study. Three Stages procedures were used. First stage, the distribution network was modelled on Electrical Transient Analyzer Program and a load flow studies was carried out using Newton Raphson Load Flow method on Electrical Transient Analyzer Program, to identify the voltage violated buses of the network. In the second stage, Optimal Capacitor Placement module on Electrical Transient Analyzer Program was used to determine the optimal locations and sizes of the capacitors. The third stage, the compensated distribution network was remodeled and another load flow studies was carried out to revalidate the results. The power factor, the voltage profile and the power losses before and after placement of capacitors was compared for revalidation. It was observed that the power factor improved by 18%, the voltage profile improved by 1.4% and the active power losses reduced by 33.1%.

KEYWORDS:Distribution System, Optimal Capacitor Placement, Power Loss, Power Factor, Voltage Profile, Reactive Power, Electrical Transient Analyzer Program (ETAP).

1. INTRODUCTION

Electric power quality is an important part of the power systems, generally meant to express the quality of voltage. Power quality improvement is the measure, analysis, and improvement of the bus voltage to maintain a sinusoidal waveform at rated voltage and frequency [1]. A distribution network with a good Power quality basically means the voltage of the network is within the generally acceptable limit (either its voltage drop is within IEC standard), since an adequate level of voltage at the receiving end terminals is essential for satisfactory operation of consumer's appliances [2].
However, most loads in a power system, are inductive in nature and hence have low lagging power factor. An inductive load with low power factor takes excessive reactive power from the network which leads to an increase in current flowing along the distribution system, as the current increases, I^2R losses along the distribution line also increases which results to a poor voltage profile at the network buses. Therefor the question of improving power factor and voltage profile to reduce line losses are paramount issues that immediately come into pictures on improvement of a power network [3].
Low power factor is distinctly undesirable because it causes poor voltage profile, increase in current, resulting in additional losses of active power in all the element of the power system from the injection station down to the utilization devices. In order to ensure most favourable conditions for a supply from engineering and economic standpoint, it is vital to have optimized power factor as close to unity as possible for a good electricity delivery [4].

Rivers State University 11kv distribution network used as a case study in this research, is a radial distribution network with 24 - 11kv buses classified as a load bus and a 33kv bus classified as a swing bus. In radial distribution network, the further away the power flow from the substation, the more voltage deceases which also leads to a poor voltage profile in addition to the voltage profile violation caused by excessive flow of reactive power in the network as a result of the low power factor of the inductive loads [5].

1.2 Problem Statement

A distribution network should deliver quality power to the end user at good voltage profile and with power losses as low as reasonably practicable. But most distribution system operate at lagging power factor because of inductive loads, lines and transformers. Power system that are inductive needs more reactive power flow from the grid. Over reactive power demand leads to increase in current (I)which result in increased power losses(I^2R), reduction in system capacity and voltage drop.

For every 1% reduction in voltage, wattage would reduce by 1.6% in filament lamp, 2% in resistive loads and 1.4 % in fluorescent. If voltage is reduced, Induction motors takes more current, leading in overheating and reduced motor life. Motor winding insulation may be weakened because of overheating, which may result to short circuit and motor burning in the long run. Due to increase in current, the line losses tend to be high which would reduce the line voltage more [6].

An improved power quality could be achieved by injecting leading reactive power through Capacitor Bank to partly or completely neutralise the lagging reactive power. Capacitor are widely used but to get effective result, it has to be optimally placed in the distribution network [7].

1.3 Research Aim

The aim of this research is to improve power quality of 11kv distribution network at a minimised cost using a case study of Rivers State University 11kv distribution network.

1.4 Research Objectives

The objectives of this research are to:

i. Model the 11kv distribution network

ii. Carry out a load flow analysis using numerical method to obtain the operating conditions of the power network parameters and ascertain the extent of voltage violation.

iii. Optimally place capacitor bank to improve power factor, voltage profile and minimized power losses.

iv. Revalidate the improved distribution network.

1.5 Scope of Work

This research focuses on the analysis and improvement of 11kv distribution system for improved power quality using Rivers State University Network as a case study.

1.6 Significance of the Study

The importance of this study is to establish a dependable data on the poor quality of Rivers State University 11kv distribution network.

2. MATERIALS AND METHODS

2.1 Materials Used for Solving the Load Flow Problems and OCP

Materials required in this research to analyse the Load Flow are; personal computer, Electrical Transient Analyser program, Bus Input Data, Line Input Data. ETAP software is used for Load Flow analyses and Optimal Capacitor Placement (OCP).

2.2 Load Flow Analysis Method

One of the most common effective computational procedures used in power system analysis is the Load Flow calculation. Load Flow studies determine the voltage (V), phase angle of voltages(δ), current (I), active power(P), reactive power (Q) and line loses (LPL) in a power system [8]. In this research, the load Flow analysis was carried out with Newton-Raphson method on ETAP Software.

2.3 Optimal Capacitor Placement Method

Many researchers had carried out work on optimal capacitor placement including Fuzzy theory, Neural Network, Partial Swarm Optimization and. This dissertation work is Genetic Algorithm based optimal capacitor placement and sizing.ETAP software 12.6 is used to evaluate the capacitor size and location in the power system network. OCP module on ETAP was used to calculate the sizes and location of the capacitors because of its extreme flexibility. The advanced graphic interface of OCP Module on ETAP provides the flexibility to control the capacitor placement process and allows the result to be view instantly. A voltage constraint of limit $95\% \leq V \leq 105\%$ and power factor constraint of limit$90\% \leq PF \leq 100\%$ was programmed on OCP module, with the violated voltage profile buses as the candidate bus for improvement.

2.4Computation of Data Required for Modelling of the Network

In order to carry out load flow analysis on any giving network with software program, it's required to model the network. This is achieved by measuring the load on each phase of the transformer station and the rout length of each bus, for effective computation of percentage loading and line parameters of the transformer stations.

2.4.1 Calculation of Transformer Loading (%)

(a) TS1-Chem/Pet Lab. Transformer Station (Rated 500KVA)

Current, $I = \dfrac{\text{Sum of all the phase readings}}{3}$ (2.1)

$$I = \frac{I_R + I_B + I_Y + I_N}{3} = \frac{267 + 294 + 321 + 103}{3} = 328.33 \text{ A}$$

Total loading= $\sqrt{3} \times V_{LL} \times I$ (2.2)

Where, V_{LL} = 378V (Measured Voltage)

Total Loading =$\sqrt{3} \times 378 \times 328.33 = 214956.34\ VA$ = 214.96 KVA

% Loading $= \dfrac{S_{VA}}{S_{MAX}} \times 100$ (2.3)

Where, S_{VA} = Total loading; S_{MAX} = Transformer Rating

% Loading $= \frac{214.96}{500} \times 100 = 42.99\%$

Table 1: Transformer Station Data of RSU 11KV Distribution Network

N/S	Transformer ID & Location	Rated Power	Measured Voltage	Phase Loads				Transformer Loading(%)
				R	B	Y	N	
1	Old Power House	1500KVA	373V	668	692	655	298	35.5%
2	TS9 – Estate &Works	500KVA	398V	305	301	283	138	47.2%
3	TS1 – Chem/Pet Lab	500KVA	378V	267	294	321	103	43.0%
4	TS2 – Elect Lab	500KVA	383V	269	263	253	157	41.7%
5	TS3 – Student Parliament	500KVA	378V	272	291	334	115	45.9%
6	TS4 – Amphitheatre	500KVA	379V	96	132	220	81	23.2%
7	TS6 – Bio lab	500KVA	384V	287	298	340	139	47.2%
8	TS8 – Road F	500KVA	376V	289	338	254	110	43.0%
9	TS 8A – Science	300KVA	382V	169	174	170	63	42.4%
10	Law	500KVA	372V	216	284	255	118	43.3%
11	Agric Farm	200KVA	369V	136	96	41	30	34.0%
12	Central Library	500KVA	365V	201	189	148	93	28.0%
13	VC's Lodge	500KVA	370V	135	178	149	82	24.5%
14	TS10 – RSU Roundabout	500KVA	385V	244	243	219	156	39.5%
15	TS12 – Senate Building	300KVA	387V	166	148	159	126	45.9%

16	Management Science	500KVA	375V	198	164	190	109	30.2%
17	Environmental Science	500KVA	372V	162	204	173	127	30.4%
18	Technical & Science	500KVA	376V	146	170	154	83	25.1%
19	Medical School	500KVA	386V	155	145	148	57	22.5%
20	NDDC Hostel	300KVA	381V	146	183	179	91	44.2%
21	Hospital	500KVA	386V	251	243	286	133	40.7%

2.4.2Calculation of Line Parameters

The conductors of the distribution network were installed overhead, and underground at some point between Transformer Stations (TS). The distributors (O/H) were arranged horizontally with the spacing of 0.86m as physically seen. This implies that D = 0.86m (O/H distributor).

(a) Per – Kilometre Resistance (R_o) for O/H distributors

$$R_o = \frac{1000\rho}{A(m^2)} \Omega/km \qquad (2.4)$$

Where ϱ = resistivity of aluminium conductor which is $2.82 \times 10^{-8} \Omega \cdot m$ at 20°C.

A = conductor cross sectional area is 158mm² ACSR/GZ

$$R_o = \frac{1000\rho}{158 \times 10^{-6} m^2} = 0.1785 \Omega/km$$

(b) Per – Kilometre reactance (Xo) for 11kv distributor (overhead)

$$X_o = 0 \cdot 1445 \, log_{10} \left(\frac{D_{GMD}}{R}\right) + 0 \cdot 0157 \, \Omega/km \qquad (2.5)$$

$$R = \sqrt{\frac{A}{\pi}} (m) = \sqrt{\frac{158 \times 10^{-6}}{\pi}} = 0.0071\text{m}$$

$$D_{GMD} = \sqrt[3]{D_{RY} \cdot D_{YB} \cdot D_{RB}} = 1.26D$$

Where D is the distance between two adjacent conductors

$$D_{GMD} = 1.26 \times 0.86 = 1.0836m$$

$$X_o = 0.1445 \, log_{10} \left(\frac{1 \cdot 0836}{0 \cdot 0071}\right) + 0.0157 = 0.331 \, \Omega/km$$

(c) Per – Kilometre Capacitive Susceptance (bo) for 11kv distributor (O/H)

$$b_o = \frac{7 \cdot 58}{Log_{10}\left(\frac{D_{GMD}}{R}\right)} \times 10^{-6} \qquad (2.6)$$

$$= \frac{7.58}{Log_{10}\left(\frac{1.0836}{0.0071}\right)} \times 10^{-6} = 3.47 \times 10^{-6} \, 1/\Omega.km$$

(d) Per Unit Value of Line parameters for Old power house Feeder (Bus 4-14)

Branch feeder from Bus 4 to Bus 14 = 0.995km

Total Impedance, $Z = (R + jX)l = (0.1785 + j0.331)0.995$

$Z = 0.178 + j0.329$

Per Unit Impedance, Z**:**

Assume: 100MVA as base MVA

11KA as base voltage

Base Impedance, $Z_b = \frac{KV_{base}^2}{MVA_{base}} = \frac{\{11KV\}^2}{100MVA} = \frac{11^2}{100} = 1.21$

Per Unit Impedance of Old Power House feeder, $Z_{(Old\ P/H)\ PU} = \frac{0.178+j0.329}{1.21}$

$Z_{(Old\ P/H)} = 0.147 + j0.272\ pu$

Per Unit Capacitive Susceptance, b_0:

$b_0 = 0.995 \times 3.47 \times 10^{-6}\ {}^{1}/_{\Omega.km} = 3.45 \times 10^{-6}\ {}^{1}/_{\Omega}$

Base admittance, $Y_b \frac{100MVA}{11KV^2} = 0.82645$

$b_{pu} = \frac{b_0}{Y_b} = \frac{3.45\times10^{-6}}{0.82645} = j4.1745 \times 10^{-6}\ pu$

$$^{b}/_{2} = 0.5 \times j4.1745 \times 10^{-6} = j0.0000021\ pu$$

Table 2: Line Parameters for RSU 11kv Distribution network

S/N	Branch Feeder/Location	Length km	Impedance $Z_{Series}(pu)$	Admittance $Y(pu)$	Susceptance $b_0/_2\ (pu)$
1.	Bus2–3 (TS9- Estate & Works Premises)	0.050	0.002 + j0.05	83.3 - j168	j(3.3×10-7)
2.	Bus2–5 (Deeper life RMU)	0.568	0.03 + j0.05	7.33 - j14.8	j(1.7×j10-6)
3.	Bus2–4 (Estate & Works Premises)	0.060	0.003 + j0.006	69.4 - j40.0	j(3.98×j10-7)
4.	Bus3–5 (NDDC Hostel)	0.370	0.018 + j0.035	11.26 - j22.7	j(2.45×j10-6)
5.	Bus 2 – 6 (TS6 – Biology)	0.520	0.025 + j0.050	8.01j - j16.16	j(3.45×j10-6)
6.	Bus2–10 (TS12 – New Senate building)	0.285	0.013 + j0.027	14.61- j29.48	j(1.87×10-6)
7.	Bus3–7 (TS1 - Chem/Pet Lab)	0.140	0.007 + j0.013	29.72 - j60	j(9.28×10-7)
8.	Bus4–24 (College of Medical Science)	0.350	0.052 + j0.096	4.35 - j8.09	j(7.35×10-6)
9.	Bus4–8 (Management Science)	0.508	0.075 + j0.139	3.01 - j5.58	j(1.07×10-6)
10.	Bus 6 – 11 (TS8A-Science)	0.280	0.013 + j0.03	15.13 - j30.3	j(1.86 ×10-6)
11.	Bus7–9 (TS2- Elect Lab)	0.165	0.008 + j0.02	25.2 - j50.9	j(1.09 ×10-6)
12.	Bus4–14 (Old Power House)	0.995	0.15 + j0.27	1.57 - j2.83	j(2.08 ×10-6)
13.	Bus9–12 (TS3 - Student Parliament)	0.154	0.007 + j0.02	27.1 - j54.6	j(1.02 ×10-6)
14.	Bus12–18 (TS4 Amphitheatre)	0.160	0.008 + j0.02	26.0 - j52.5	j(1.06 ×10-6)
15.	Bus18–20 (TS8- Road F)	0.196	0.01 + j0.02	17.6 - j35.4	j(1.30 ×10-6)
16.	Bus10–15 (TS10- RSU Round-About)	0.180	0.009 + j0.02	23.1 - j46.7	j(1.19 ×10-6)
17.	Bus8–13 (Environmental Science)	0.460	0.068 + j0.13	3.3 - j6.16	j(9.66 ×10-7)
18.	Bus11–17 (Hospital)	0.270	0.04 + j0.07	5.7 - j10.5	j(5.67 ×10-7)

19.	Bus11–16 (Faculty of Law)	0.230	0.034 + j0.06	6.6 - j12.3	j(4.83 ×10^{-7})
20.	Bus16–21 (VC's Lodge)	0.320	0.047 + j0.09	4.8 - j8.9	j(6.72 ×10^{-7})
21.	Bus21–22 (Agric Farm.)	0.180	0.032 + j0.06	7.01 - j13.0	j(3.78 ×10^{-7})
22.	Bus22–23 (Central Library)	0.360	0.053 + j0.10	4.24 - j7.9	j(7.56 ×10^{-7})
23.	Bus13–19 (Technical & Science)	0.420	0.062 + j0.12	3.64 - j6.7	j(8.82 ×10^{-7})

2.5 Modelling of RSU 11kv Distribution Network

Fig1 shows the One -line diagram of RSU 11KV distribution network modelled on ETAP. It comprises 1-33kv bus and 24-11kv bus. The bus system has an injection substation, whose bus is characterised as Swing (Slack) bus and 24 load (PQ) buses.

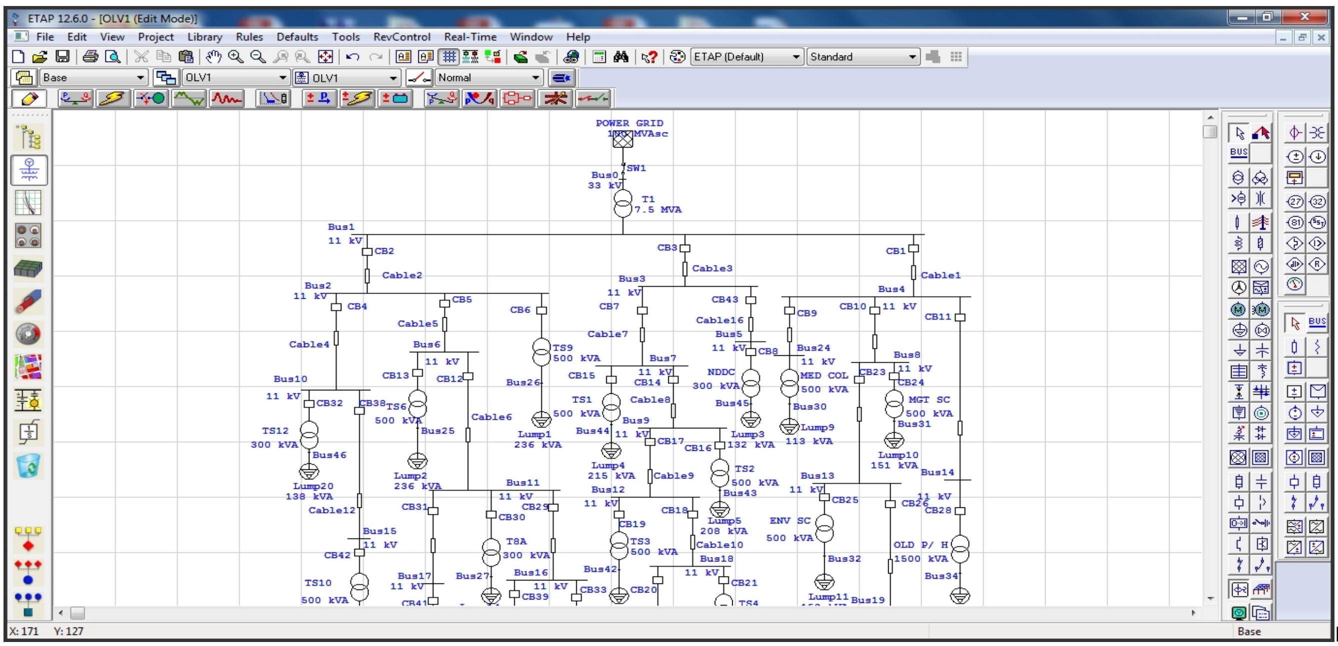

Fig1 ETAP View of One-Line Diagram of RSU 11KV Distribution Network.

3. RESULTS AND DISCUSSION

3.1 Load Flow Analysis before Optimal Capacitor Placement

The Load flow studies carried out on the distribution system reviewed that there was voltage violation at all the buses. Bus13, Bus14, Bus16, Bus21, Bus22, and Bus23 were critically under voltage while the remaining 18 buses were marginally under voltage.

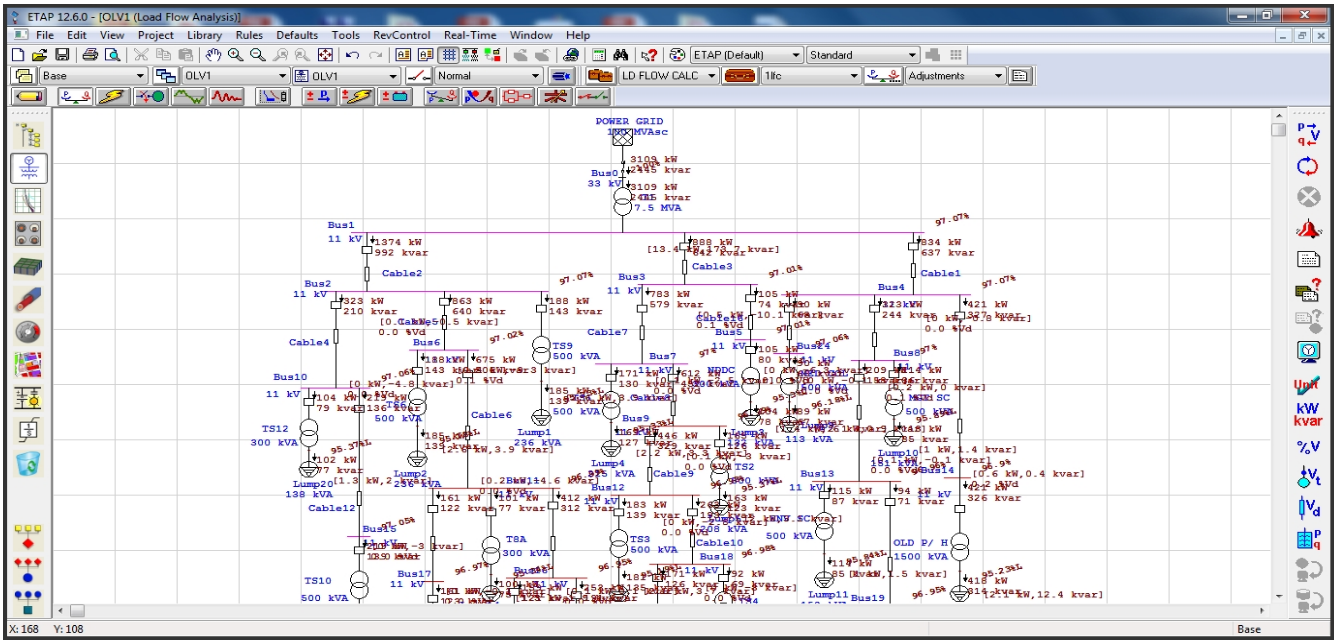

Fig 2 ETAP View of Load Flow Results of RSU Network

Out of the total power of 3118.4 KW demanded, 48.3KW were calculated as active power losses along the distribution system and Transformer. This is shown on fig 3 below.

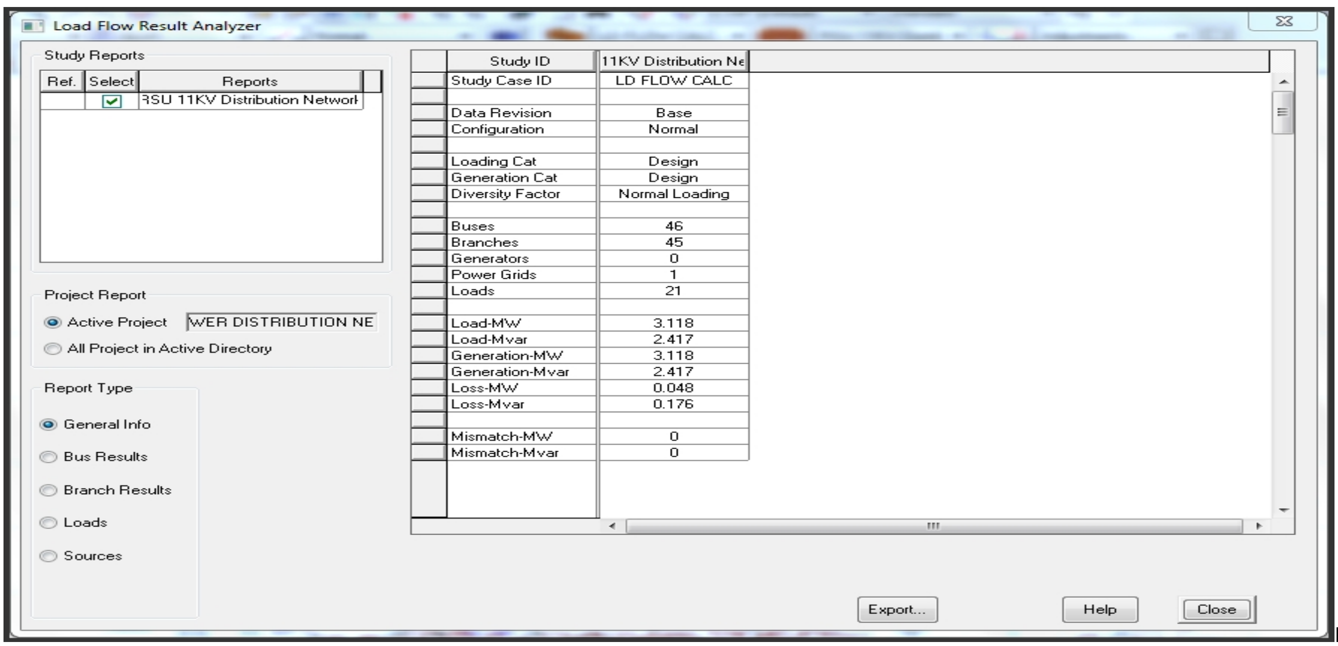

Fig 3

ETAP View of Load Flow Result Analyzer before OCP

3.2 Optimal Capacitor Placement Simulation

A voltage constraint of limit $95\% \leq V \leq 105\%$ and power factor constraint of limit $90\% \leq PF100\%$ was programmed on the OCP module on ETAP, with the violated voltage profile buses as the candidate bus for improvement. The optimal capacitor placement converges in 720 seconds and a total of 1900KVar capacitors was proposed for 19 buses. Fig 4 shows ETAP view of the optimal capacitor placement results.

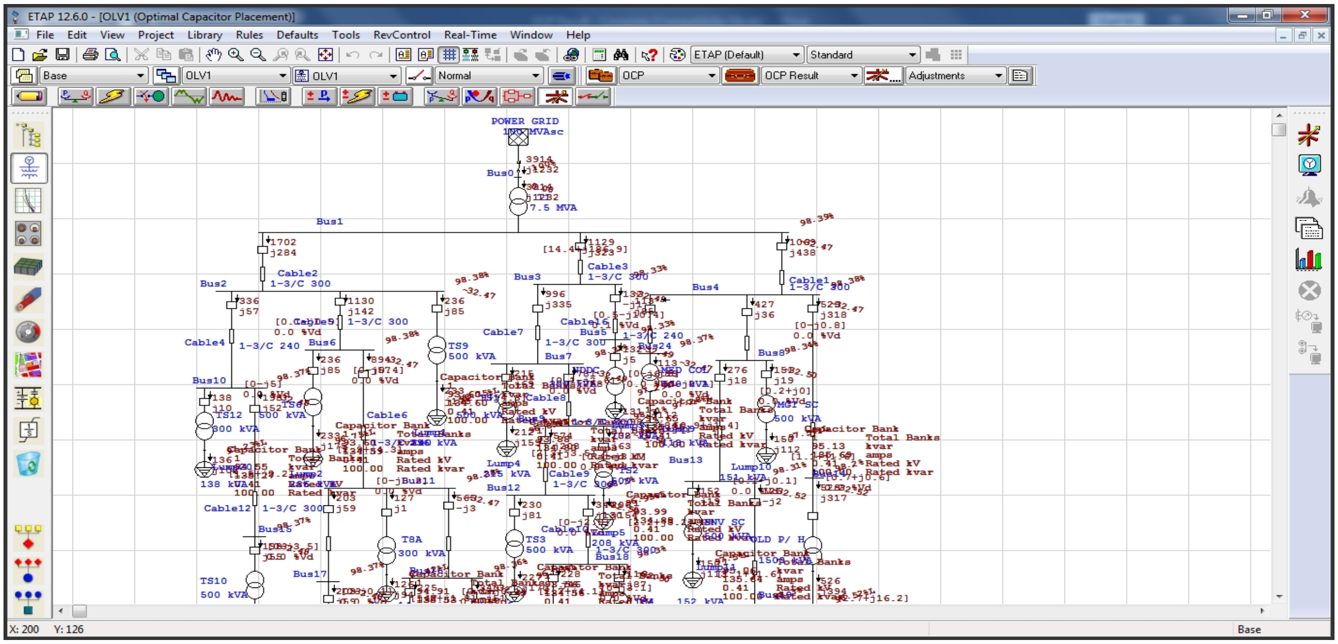

Fig 4: ETAP View of Optimal Capacitor Placement Results of RSU Network

3.3 Revalidation of the Improved Network

3.3.1 Remodelling of RSU Distribution Network with Placed Capacitor Banks

After OCP Simulation, the distribution network with proposed capacitors placed was remodelled. Fig 5shows ETAP view of the remodelled network with 19 placed capacitors as sized and located with OCP module on ETAP.

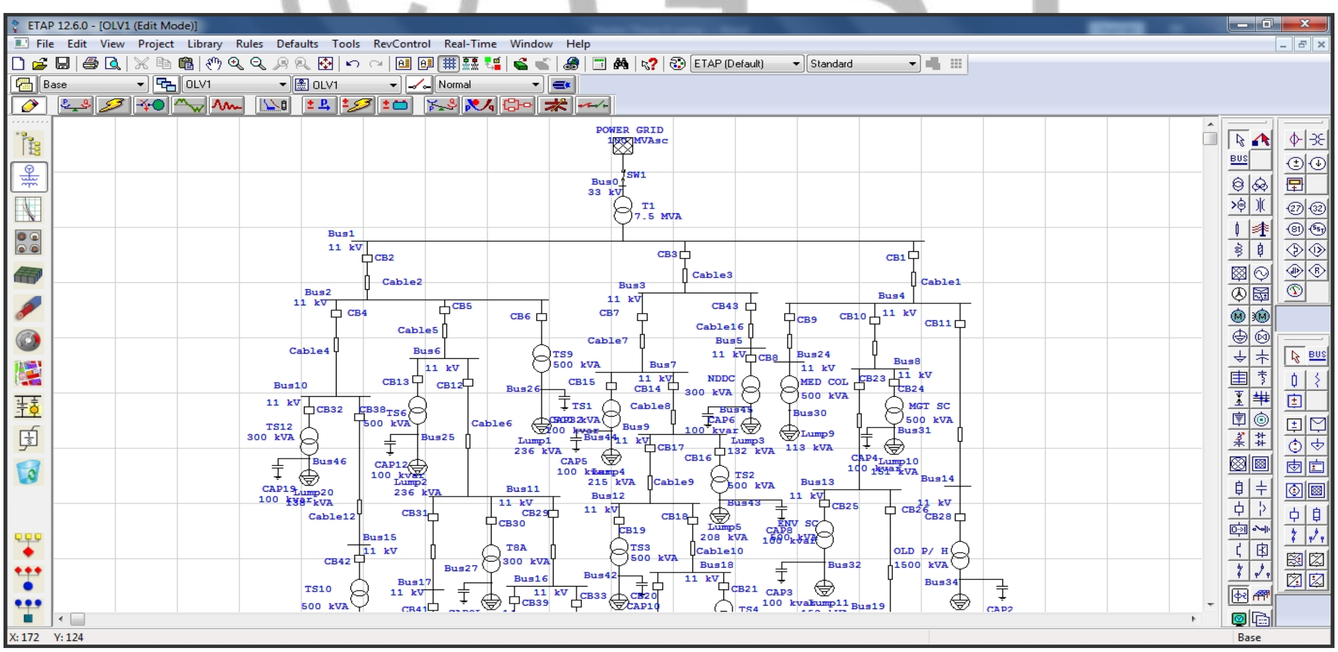

Fig 5 ETAP View of Remodelled RSU Network with capacitors placed.

3.3.2 Load Flow Analysis after Optimal Capacitor Placement

Load flow studies was conducted on the remodelled compensated network to revalidate the improved network. The ETAP view of the load flow calculation results is shown in Fig 6.

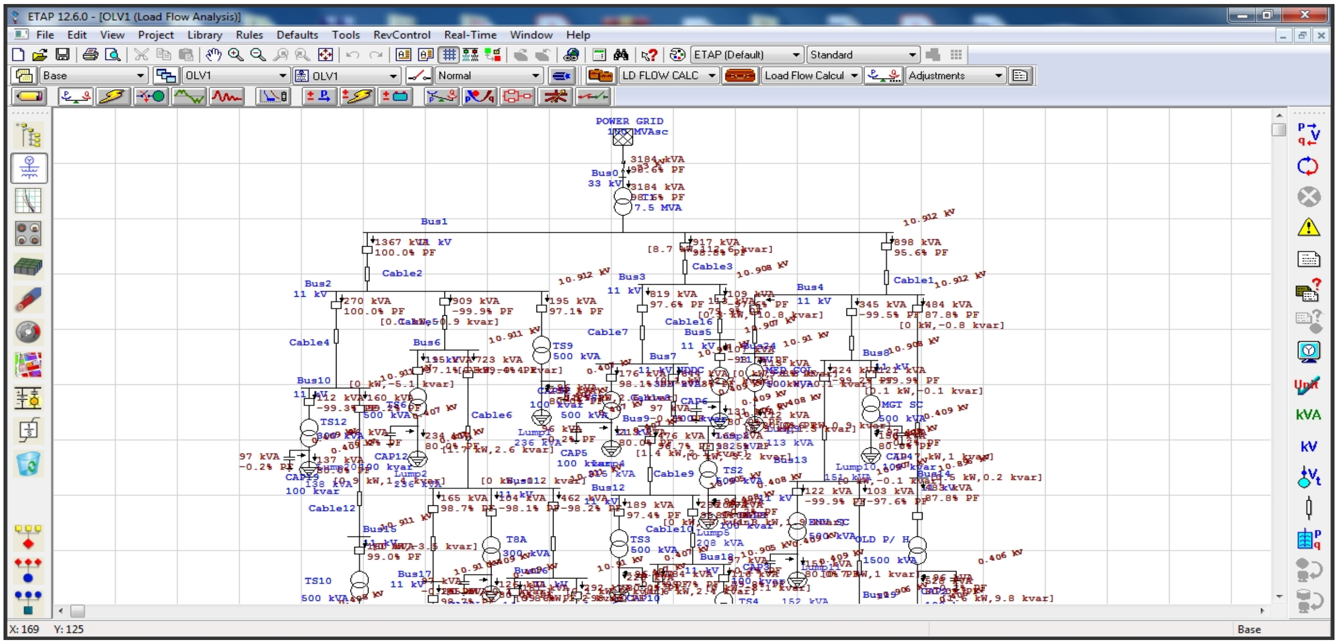

Fig 6 ETAP View of Load Flow Results of RSU Network after OCP

The Load flow studies carried out to revalidate the remodelled network, reviewed that Bus13, Bus14, Bus16, bus21, Bus22 and Bus23 that were critically under voltage before capacitor placement, improved by 2.2%, 2.7%, 2.2%, 2.3%, 2.3%, and 2.3% respectively. The power factor of Bus13, Bus14, Bus16, Bus 21, Bus 22, and Bus23 also increased by 19.4%, 8.8%, 14.5%, 10.4%, 7.8% and 13.6% respectively. The total active power losses along the distributors and transformers reduced by 33.1%.
The increase in power factor, and the power losses reduction was as a result of the reactive power being compensated by optimally placed capacitor banks on the network. The leading reactive power injected into the network through the capacitor bank partly neutralised the lagging reactive power of the network which reduced the excessive lagging current drawn by the network inductive loads and subsequently reduced the losses in the distribution apparatus (distribution lines and transformers). Fig 7 below is the ETAP view of the Load Flow Result Analyzer, showing the total active power losses after reactive power compensation.

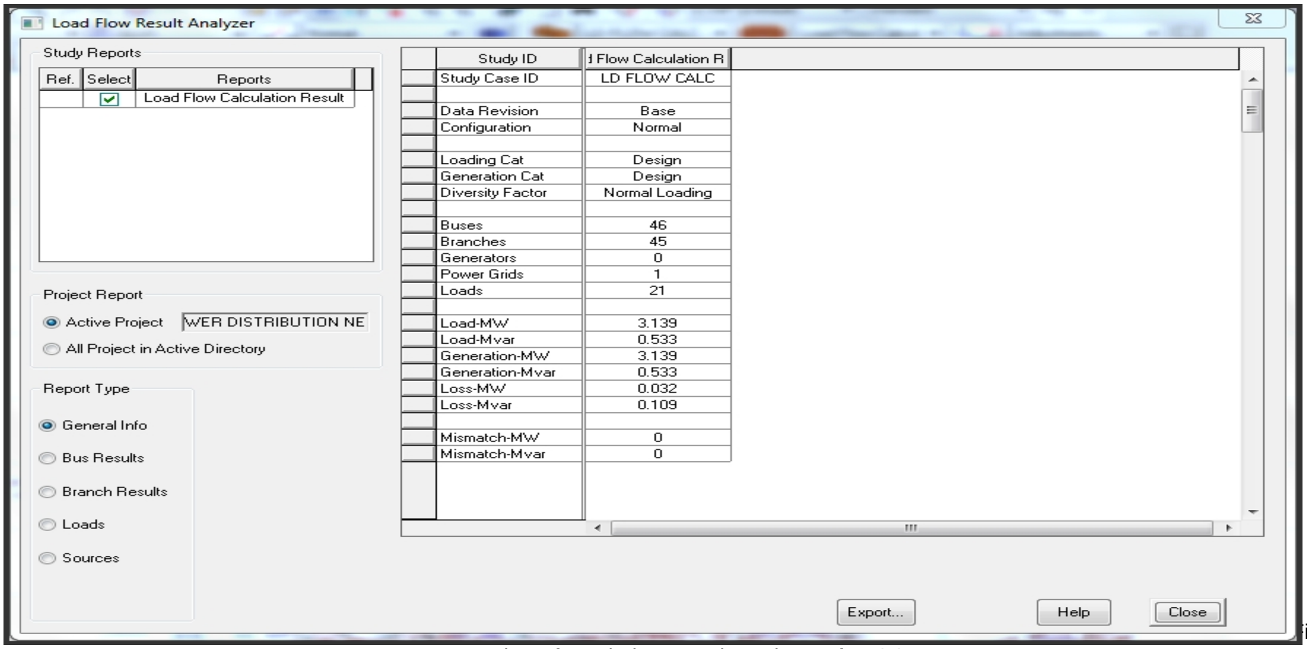

Fig 7: ETAP View of Load Flow Result Analyzer after OCP

3.3.3 Comparison of Bus Parameters

The bus parameters before and after placement of capacitor was compared to ascertain the extent of improvement. Table 3 and Table 4 illustrate the difference in Voltage and power factor, and power Loss respectively while Fig 8, Fig 9, and Fig 10 shows the respective graphical illustrations.

Table 3: Comparison of Bus Voltage before and after OCP

Bus ID	Voltage before OCP (KV)	Voltage before OCP (Pu)	Voltage after OCP (KV)	Voltage after OCP (Pu)	P.F before OCP (%)	P.F after OCP (%)
0	33.000	1.0000	33.000	1.0000	79.0	98.6
1	10.682	0.9711	10.912	0.9920	81.1	99.1
2	10.681	0.9710	10.912	0.9920	81.4	99.9
3	10.675	0.9705	10.908	0.9916	81.6	98.1
4	10.681	0.9710	10.912	0.9920	79.4	94.4

5	10.674	0.9704	10.907	0.9915	79.6	98.7
6	10.675	0.9705	10.911	0.9919	81.5	99.6
7	10.674	0.9704	10.907	0.9915	81.4	97.5
8	10.673	0.9703	10.908	0.9916	79.8	99.5
9	10.672	0.9702	10.906	0.9915	81.7	97.2
10	10.680	0.9708	10.911	0.9919	80.1	99.7
11	10.672	0.9702	10.911	0.9919	81.8	98.9
12	10.671	0.9701	10.905	0.9914	82.2	96.5
13	10.669	0.9699	10.907	0.9915	79.8	99.2
14	10.662	0.9693	10.896	0.9905	79.0	87.8
15	10.680	0.9709	10.911	0.9919	79.7	99.0
16	10.668	0.9698	10.910	0.9918	83.0	97.5
17	10.670	0.9700	10.910	0.9918	79.7	98.7
18	10.671	0.9701	10.905	0.9914	83.5	95.6
19	10.667	0.9697	10.906	0.9915	79.8	97.6
20	10.670	0.9700	10.904	0.9913	84.6	99.5
21	10.664	0.9695	10.909	0.9917	83.0	93.4
22	10.663	0.9694	10.909	0.9917	83.2	91.0
23	10.661	0.9692	10.908	0.9916	84.7	98.3
24	10.680	0.9709	10.910	0.9918	79.8	86.8

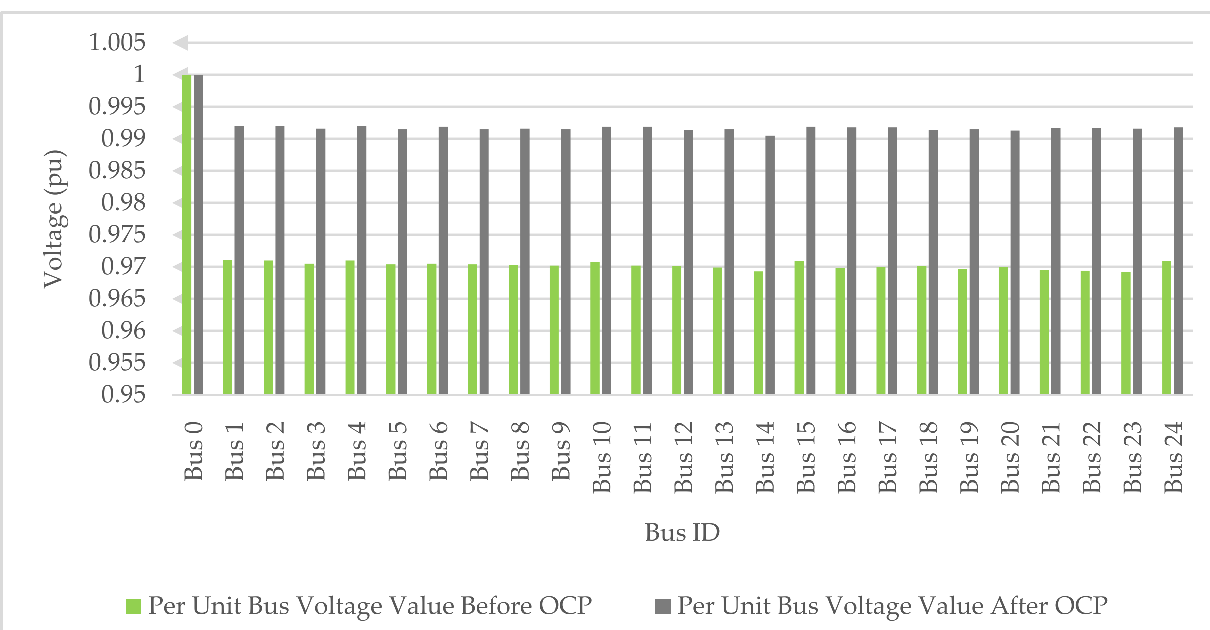

Fig 8: Bus Voltage Comparison

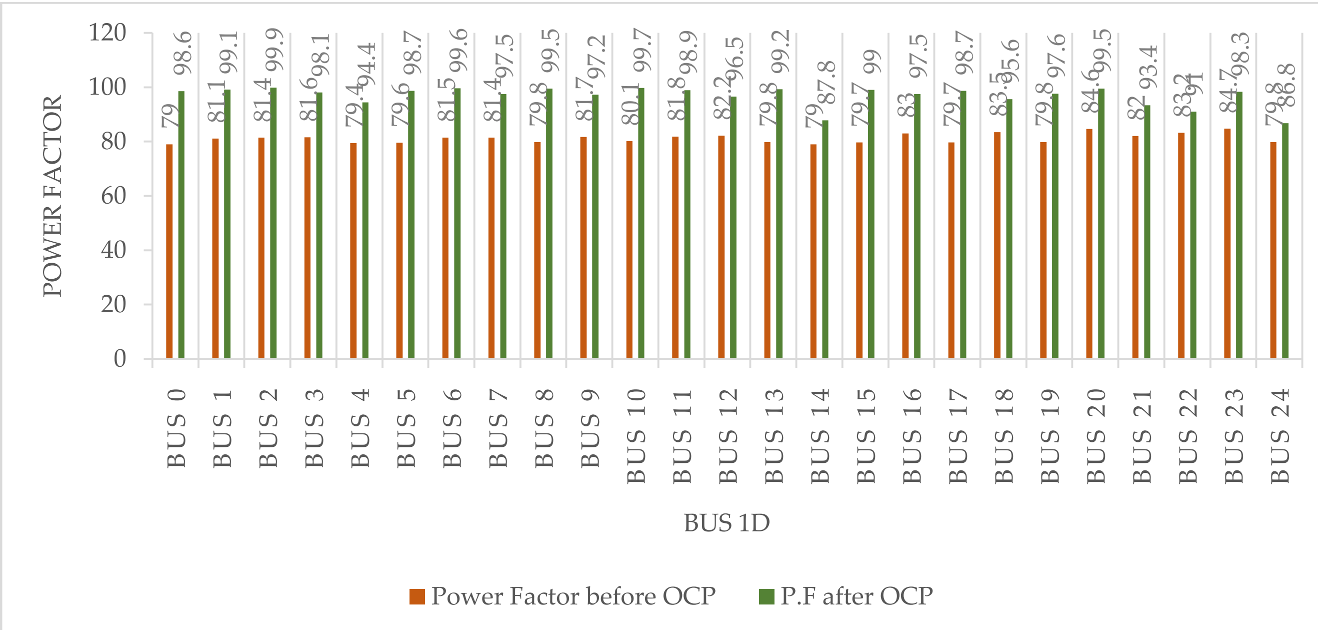

Fig 9: Comparison of Bus Power Factor before and after OCP

Table 4: Comparison of Bus Power Losses before and after OCP

Total Power Losses before OCP		Total Power Losses after OCP	
KW	**KVar**	**KW**	**KVar**
48.3	175.8	32.3	108.6

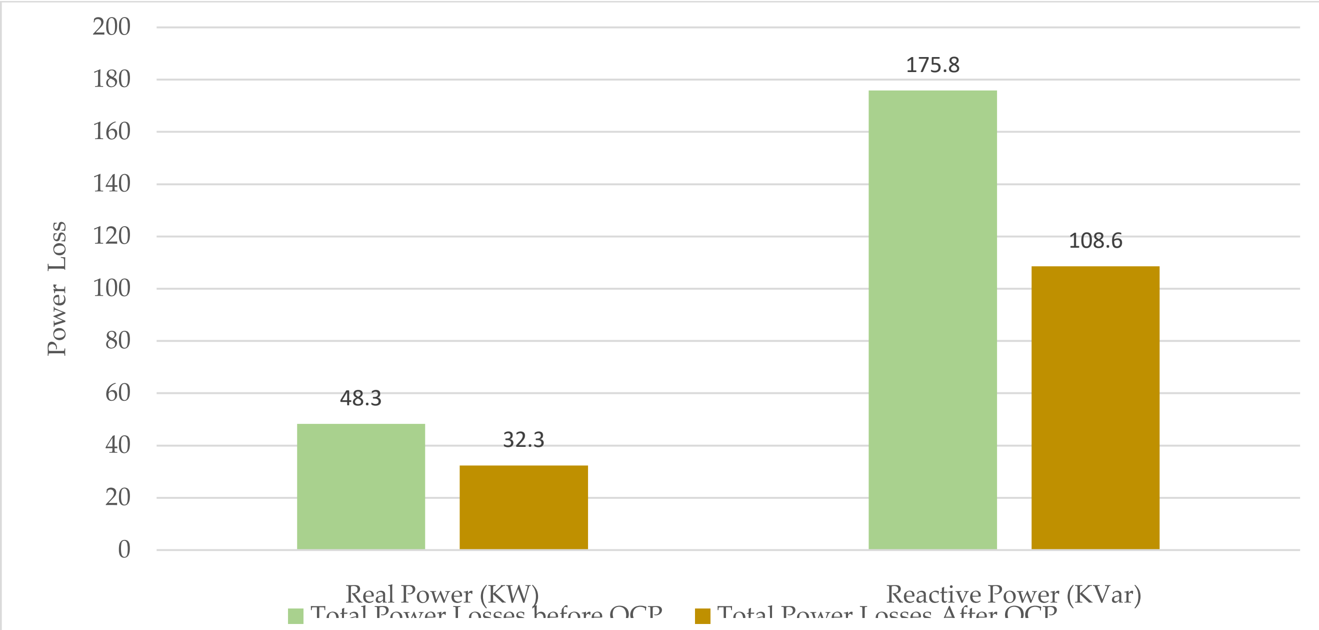

Fig 10: Comparison of Power Loss before and After OCP

4.CONCLUSION

The objectives of this research were accomplished by modelling the 11kv distribution network of Rivers State University, which was used as a case study. Load Flow analysis carried out to study voltage profile violation of the network, reviewed that Bus13, Bus14, Bus16, Bus21, Bus22, and Bus23 were critically under voltage. Optimal capacitor Placement conducted on the network calculated 1900KVar capacitors to improve the network. The compensated network was remodelled and another load flow study was carried out to revalidate the improved network. It was observed that the capacitors placed on the network injected a leading reactive power to partly neutralised the lagging reactive power which subsequently;

i. Improved the power factor of Bus13, Bus14, Bus16, Bus21, Bus22, and Bus23 by 19.4%, 8.8%, 14.5%, 10.4%, 7.8% and 13.6% respectively.

ii. Reduced the total active power losses by 33.1% (16KW).

iii. Improved the voltage profile of Bus13, Bus14, Bus16, Bus21, Bus22 and Bus23 that were critically under voltage by 2.2%, 2.7%, 2.2%, 2.3%, 2.3%, and 2.3% respectively.

Conclusively, Optimal Capacitor Placement in RSU distribution network shows that placement of capacitor optimally in 11kv distribution network improve power quality of a network.

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