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Minimization of Power Loss in Electrical Network by Incorporating Distributed Generator and Capacitor (Case Study: Salvation Ministries Cathedral)

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Abstract
This paper addresses power loss minimization in the Salvation Ministries Cathedral distribution network, initially at 0.85pu power factor. Simulation and modeling in ETAP with Newton Raphson load flow reveal undervoltage in multiple buses due to network overloading. To mitigate this, DG units (1500KW at bus 56, 1500KW at bus 58, 1700KW at bus 50) and capacitors (2930KVAR at bus 10, 400KVAR at bus 54) were optimally placed based on the new power factor. Voltage profiles significantly improved, raising impacted buses to acceptable levels. Concurrent installation of DG and capacitors also reduced active power loss from 238KW to 92.5KW (61% drop) and reactive power loss from 1093KVARr to 360KVAR (78% reduction), improving the network's power factor to 0.96pu. This approach effectively minimized power losses and enhanced the distribution network's operational efficiency.

Keywords- *Distributed generator, capacitor Bank, power loss, voltage profile, undervoltage, ETAP*

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I. INTRODUCTION

Power flow in electrical systems leads to significant power loss, voltage drops along the lines, and poor power factor at the load terminals. Power losses in electrical systems occur due to various factors such as resistance in transmission lines, distribution system, transformers, and other electrical components. These losses contribute to reduced efficiency, poor voltage profile, poor power factor at load centers, increased operating costs, and environmental impacts. [1]

Minimization of power losses in an electrical network is a crucial aspect of maintaining a highly efficient and reliable power system. One solution to these problems involves the integration of Distributed Generation DG and capacitors in to the electrical network. [2]

Integrating capacitors into electric systems reduces power losses, enhance the voltage profile and improve system power factor. A low power factor indicates that a significant portion of the distributed power is wasted as a result of reactive power flow, leading to increase in power loss. [3]

The problem associated with capacitor placement is to determine the optimal size and location of capacitor where power loss is minimum and cost saving is maximum [4]. In this research, a simulation and modelling technique is used to determine the optimal size and location of capacitor since it gives more practical and simple results.

Distributed Generation (DG) units which are known by various names such as decentralized generation, dispersed generation, and embedded generation, refers to small scale power generation facilities that are directly interconnected to the distribution network or located at the costumer's premises. [5]

Distributed Generation has become increasing important in the field of the power sector due to its high efficiency, compact size, low investment cost, and its ability to harness renewable energy resources. The concept of installing DG units near load centers has been around for the past few years, but with the rise of retail electricity markets and the push for renewable energy sources like solar PV, biomass gasifiers and wind turbine, as well as non-renewable sources such as fuel cells, internal combustion engines (ICE), and microturbines, its importance has increased.

The global trend in recent years which has seen a rise in the adoption of Distributed Generation resources both renewable and non- renewable, has been aided by national and international policies that aim to boost the utilization of renewable energy resources and highly efficient micro-combined heat and power units to combat greenhouse gas emission and mitigate the impact of global warming. [2]

WHY DISTRIBUTED GENERATION

In the last decade, a renewed focus on Distributed Generation DG has emerged as a result of technological advancement and changes in the economic and regulatory landscape. This is confirmed by the IEA, who highlighted five major factors contributing to this evolution, including advancements in distributed generation technologies, constraints on the construction of new transmission and distribution lines, growing consumer demand for reliable electricity, electricity market liberalization, and concerns about climate change [2]. However, it is believed that the main driving forces behind this shift can be simplified in to electricity market liberalization and environmental consideration. Though the development in DG technologies have been in existence for some time, they have not been able to disrupt the traditional economies of scale model. It is unlikely that DG units will totally replace the need for new transmission lines as the grid still has to be available as backup supply. [6]

Electricity suppliers are increasingly interested in Distribution Generation as they view it to be a means to cater for specific market niches in a liberalized environment. DGs are generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in the power system. DG units includes synchronous generators, induction generators, reciprocating engines, combustion gas turbines, micro-turbines, solar photovoltaic, wind turbines, fuel cells, and other small power sources. DGs can provide cost-effective, environmentally friendly, high power quality and more reliable energy solutions than a conventional generation [7]. Optimal DG allocation secures distribution system from unwanted events and allows the operator to run the system in island mode [8]

Distribution Generations can broadly be classified in to four types based on their capability to deliver real and reactive power in to the electrical network. [9]

i. Type 1: This type of DG units are only capable of delivering active power in to the electric system such as micro-turbines, photovoltaic, fuel cells. This DG units can be integrated in to the main grid with the help of converters/inverters. Additionally, photovoltaic can sometimes be employed to provide reactive power as well.
ii. Type 2: DG capable of delivering both active and reactive power. DG units based on synchronous machines (cogeneration, gas turbine, etc.) come under this type.
iii. Type 3: DG capable of delivering only reactive power. Synchronous compensators such as gas turbines are examples of this type and operate at zero pf.
iv. Type 4: DG capable of delivering active power but also consuming reactive power. Mainly induction generators used in wind farms come under this class.

In this paper, type 1 and type 2 are taken in to consideration.

CAPACITOR PLACEMENT

Optimal placement of capacitors within the electrical network is essential to minimize this power losses, improve power factor and enhance the overall system performance.

Several factors are to be considered when determining the optimal capacitor placement in electrical systems. One key consideration is the proximity of the capacitors to the load centers. Placing capacitors near the loads they support reduces the length of the connecting wires, thereby reducing the inductance and resistance in the electrical network. This also ensures that the stored energy in the capacitor is delivered to the loads they support, reducing power losses in the process.

Additionally, capacitor placement in relation to the power source is essential in order to minimize power losses. Capacitors should be located near the power source to reduce the length of connections and minimize energy losses during transmission and distribution. Hence, strategic placement ensures that capacitors can effectively mitigate fluctuations in voltage and power factor. [10]

Power Factor

Power factor is the ratio of Active Power (P) to the Apparent Power (S) as shown in Fig. 1

$$\text{Power factor} = \frac{Active\ power\ (W)}{Apparent\ power\ (KVA)} = \frac{P}{S} = \frac{S\ Cos\ \theta}{S} = cos\ \theta \quad (1)$$

The original power factor of the proposed network is 0.85 (i.e 85%)

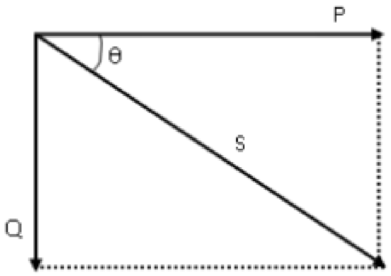

Figure 1: Power diagram

Inductive components, such as ballasts, draw reactive power, Q (Var) from the mains. It lags behind the Active Power, P (W) by 90° (Figure 2.1). A capacitor, if connected across the mains, will also draw reactive power, but it leads the active power by 90°. The direction of the capacitive reactive power (Q_C) is opposite to the direction of the inductive reactive power (Q_L) (Figures 2 and 3)

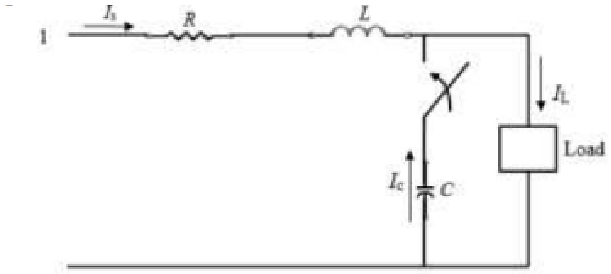

Figure 2: Capacitive power loss reduction

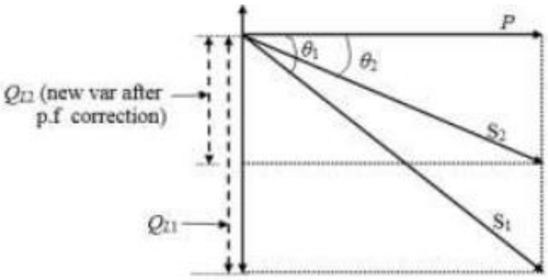

Figure3: Phasor diagram of figure 2

If a capacitor is connected in parallel with an inductive load, it will draw capacitive leading reactive power. The effective reactive power drawn by the circuit will reduce to the extent of the capacitive reactive power, resulting in reduction of apparent power from S_1 to S_2. The phase angle between the active power and the new apparent power S_2 will also reduce from θ_1 to θ_2 (Fig. 2.3). Thus the power factor will increase from $\cos\theta_1$ to $\cos\theta_2$. The reactive power supplied by the capacitor is thus given by:

$$Q_C = Q_{L1} - Q_{L2} = P(\tan\theta_1 - \tan\theta_2) \quad (2)$$

$$KVAr = W(\tan\theta_1 - \tan\theta_2)$$

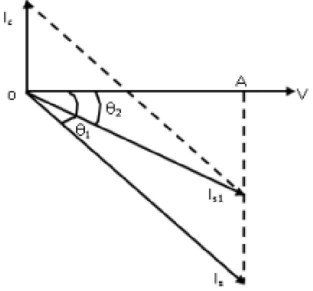

Figure4: Current phasor diagram for figure 2

After compensation (capacitor is switched on) $\mathbf{I}_s$ decreases to $\mathbf{I}_{s1}$ i.e., reactive component of $\mathbf{I}_s$ decreases from $I_s \sin \Theta_1$ to $I_{s1} \sin \Theta_2$

$I_c = I_s \sin \Theta_1 - I_{s1} \sin \Theta_2$

MATERIALS AND METHODS

Materials Gathered

i. Existing single line diagram (SLD) of Salvation Ministries Cathedral
ii. Distribution line data
iii. load data: data of existing and projected load profile of network.
iv. software: ETAP 19.0.1c

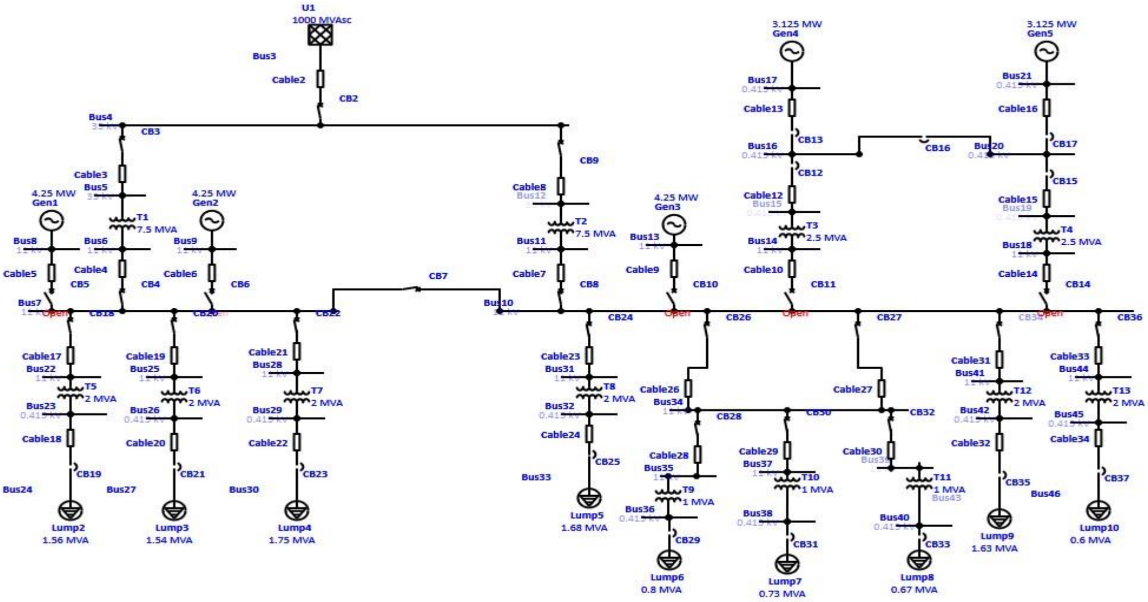

Fig 5: Single line diagram of the Electrical Network, Salvation Ministries Cathedral (Base case without DG and Capacitor placement)

Method used

This project employed ETAP to perform load flow analysis on the Salvation Ministries Cathedral Electrical network (base case) using Newton Raphson technique

****Note;** "Base case" is the existing condition of the system under study, that is Salvation Ministries Cathedral Electrical network before the placement of Distributed Generator DG and capacitor to minimize power loss.*

Below is a flow chart of the sequence of activities performed in this project.

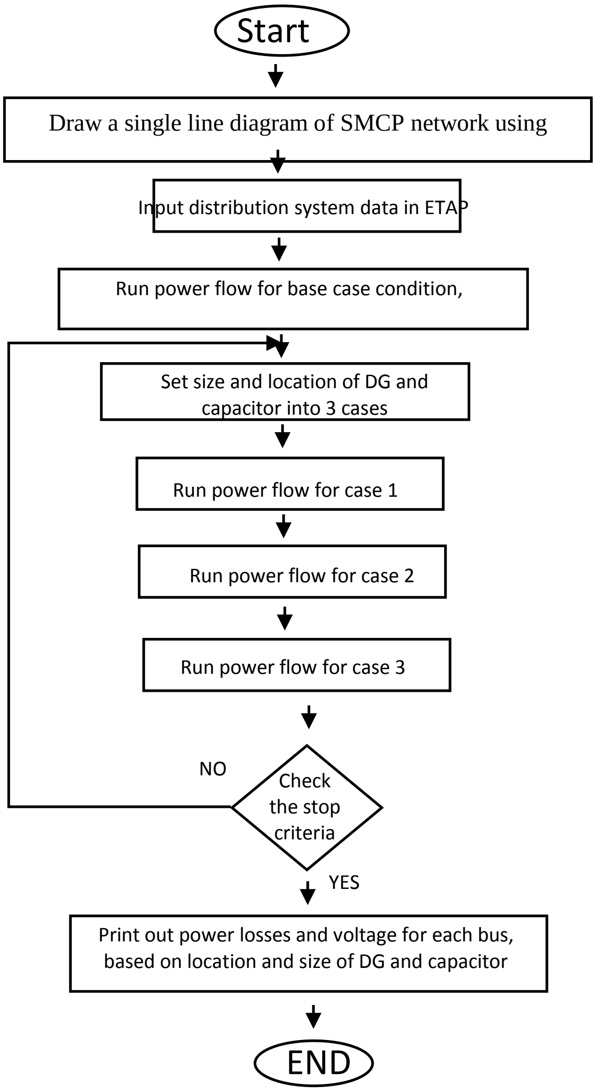

Fig 6: shows the simulation flow chart for DG and capacitor placement

Newton Raphson Equation for Load Flow Analysis:

The net current injected into the network at i^{th} bus:

$I_i = Y_{i1}V_1 + Y_{i2}V_2 + \cdots + \cdots Y_{iN}V_N = \sum_{k=1}^{N} Y_{ik}V_k$(3.1)

$I_i = \sum_{k=1}^{N}|Y_{ik}|\,|V_k|\angle\theta_{ik} + \delta_k$(3.2)

The Apparent power at i^{th} bus is:

$S_i = P_i - jQ_i = V_i I_i$(3.3)

$P_i - jQ_i = |V_i|\angle\text{-}\,\delta_i \sum_{k=1}^{N}|Y_{ik}|\,|V_k|\angle\Theta_{ik} + \delta_k$ (3.4)

The real and imaginary parts are separated;

$P_i = V_i \sum_{k=1}^{n} V_k\, Y_{ik} \cos(\theta_{ik} + \delta_k - \delta_i\ )$ (3,5)

$Q_i = -V_i \sum_{j=1}^{n} V_k\, Y_{ik} \sin(\theta_{ik} + \delta_k - \delta_i$ (3.6)

Constraints:

Bus Voltage Limits:

$0.95 \le V_i \ge 1.05, i = 1,2,3 \ldots\ldots\ldots. N\ bus$ (3.7)

DG Power Factor Limit:

$0.8 \le PF \ge 1$(3.8)

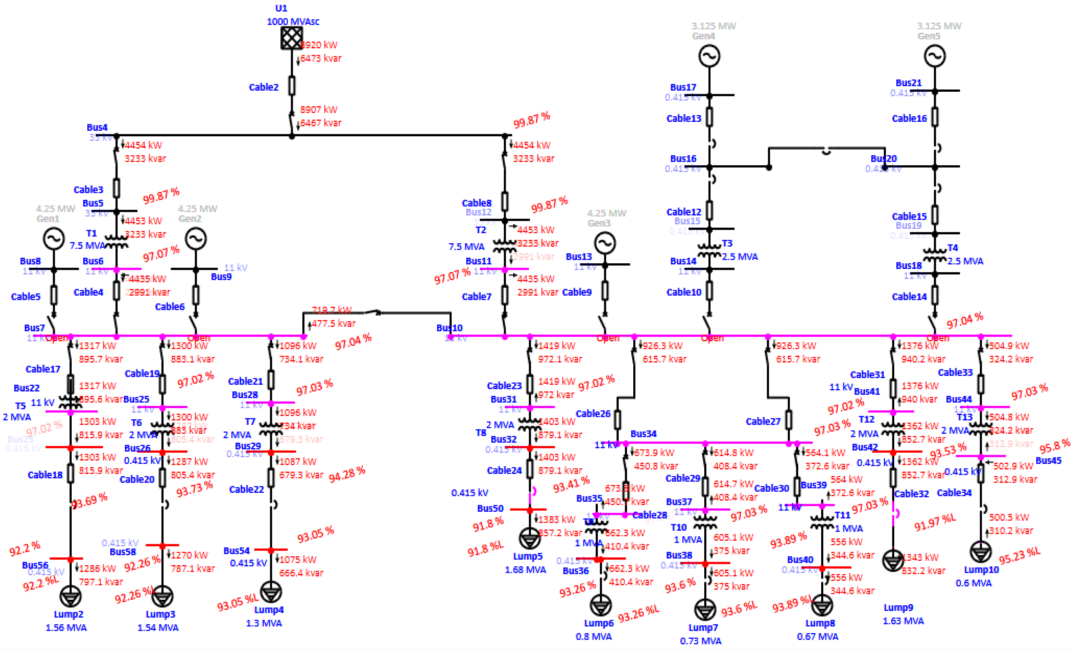

Fig 7: Load flow of the base case in ETAP without DG and capacitor placement

Figure 3.3 shows the voltage profile of the base case. Buses with red color are said to be experiencing under voltage condition (that is voltage level below 0.95pu of the rated bus voltage). To remedy this situation, DG units and capacitor bank will be integrated in to the base case to evaluate their effect on buses with under voltage condition.

Cases Tested:

The simulation of DG and Capacitor placement was tested with three different cases.

1. Case 1: only capacitor placement
2. Case 2: only DG placement
3. Case 3: incorporating DG and Capacitor simultaneously.

Case 1: only capacitor placement

The sizing and placement of capacitor in to the base case was carried out. The determination of the size and location of capacitor was based on the voltage profile of the base case as shown in figure 3.2, with bus 10 and bus 54 chosen as optimal location for capacitor placement after examining their impact if placed on the other buses in the network.

Determination of capacitor size for bus 10:

Given;

$$S = \sqrt{3}V_l I_l = 10.51MVA$$
$$P = \sqrt{3}V_l I_l \cos\Theta_1$$
$$\cos\Theta_1 = 0.85$$
$$\cos\Theta_2 = 0.96$$
$$Q_C = ?$$

Where;

S = Apparent power of the base network in MVA

P = is the total real power of the base network in MW

$\cos\Theta_1$ = is the existing power factor (pf) of the base network

$\cos\Theta_2$ = is the new power factor (pf)

$$Q_C = Capacitive\ reactive\ power\ in\ Mvar\ for\ 11kv\ bus$$

Hence,

$$P = 10.51 \times 0.85 = 8.9335MW$$
$$\Theta_1 = \cos^{-1}(0.85) = 31.7883^0$$
$$\Theta_2 = \cos^{-1}(0.96) = 16.2602^0$$

Recall;

$$Qc = P(\tan\Theta_1 - \tan\Theta_2) \quad (31)$$

$$Q_C = 8.9335MW(\tan 31.7883 - \tan 16.2602)$$

$$Q_C = 8.9335MW(0.6197 - 0.2917)$$

$$Q_C = 2.93Mvar$$

$$Q_C = 2930KVAR$$

Considering the sizes of capacitor bank available in the market, 2930KVAR can be expressed in multiples of 5. That is

$$2930KVAR \div 5 = 586 \cong 600KVAR$$

$$Q_C = 5 \times 600KVAR$$

Similarly,
For bus 54:
Given;
Bus apparent power S= 1.3MVA

$$P = 1.3 \times 0.85 = 1.105MW$$

$$\cos \Theta_1 = 0.85$$

$$\cos \Theta_2 = 0.96$$

$$Q_C \; for \; bus \; 54 = ?$$

Hence,

$$Q_C = 1.105MW(0.6197 - 0.2917)$$

$$Q_C \; for \; bus \; 54 = 0.36224MVAR$$

$$Q_C = 362.24KVAR \cong 400KVAR$$

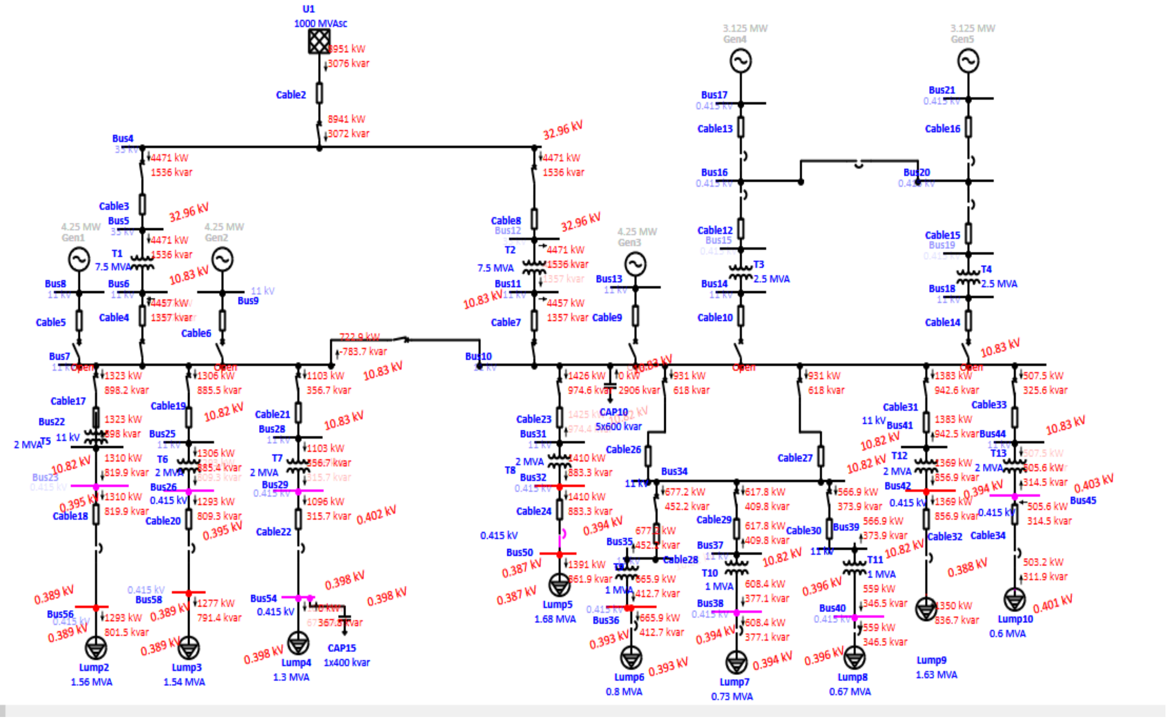

Fig 8: load flow of base case after capacitor placement

Case 2: Only DG placement

The size and placement of DG was based on the power requirement of the load.

Three DG units were placed at three different buses. Buses experiencing high level of under voltage condition were given maximum priority. Bus 50, bus 56 and bus 58 were chosen as the optimal location for DG placement due to their high level of under voltage condition

DG unit with rating of 1500KW was placed in bus 56 with load of 1.5MVA

DG unit with rating of 1500KW was placed in bus 58 with a load of 1.54MVA

DG unit with rating of 1700KW was placed in bus 50 with a load of 1.68MVA

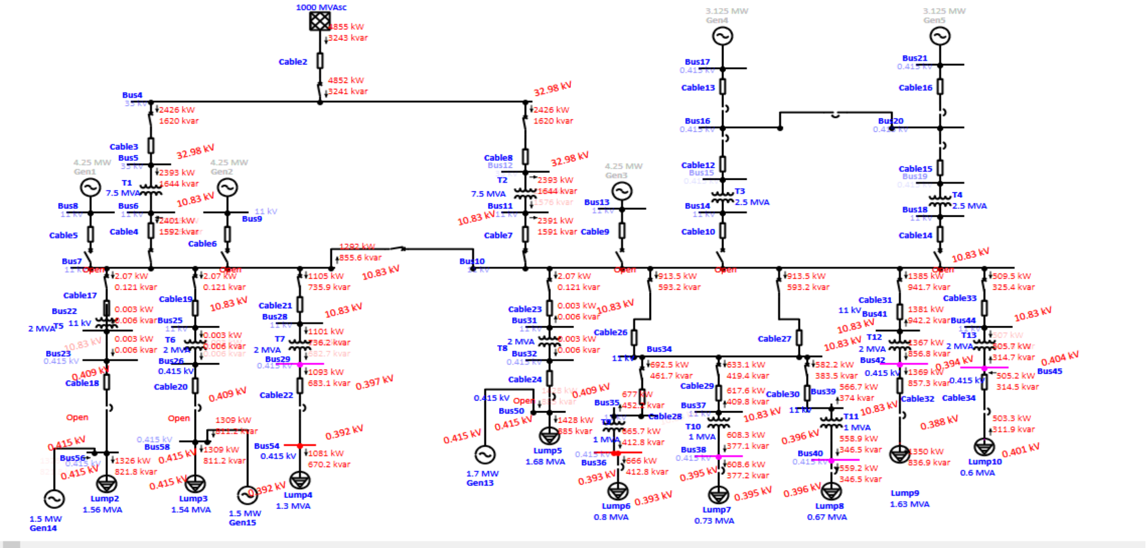

Fig 9: Load flow of base case with only DG placement

Case 3:incorporating DG and Capacitor simultaneously

DG units and capacitors with the same size and rating as when they are placed individual were incorporated in to the base case simultaneously to evaluate their effect on the voltage profile of the network.

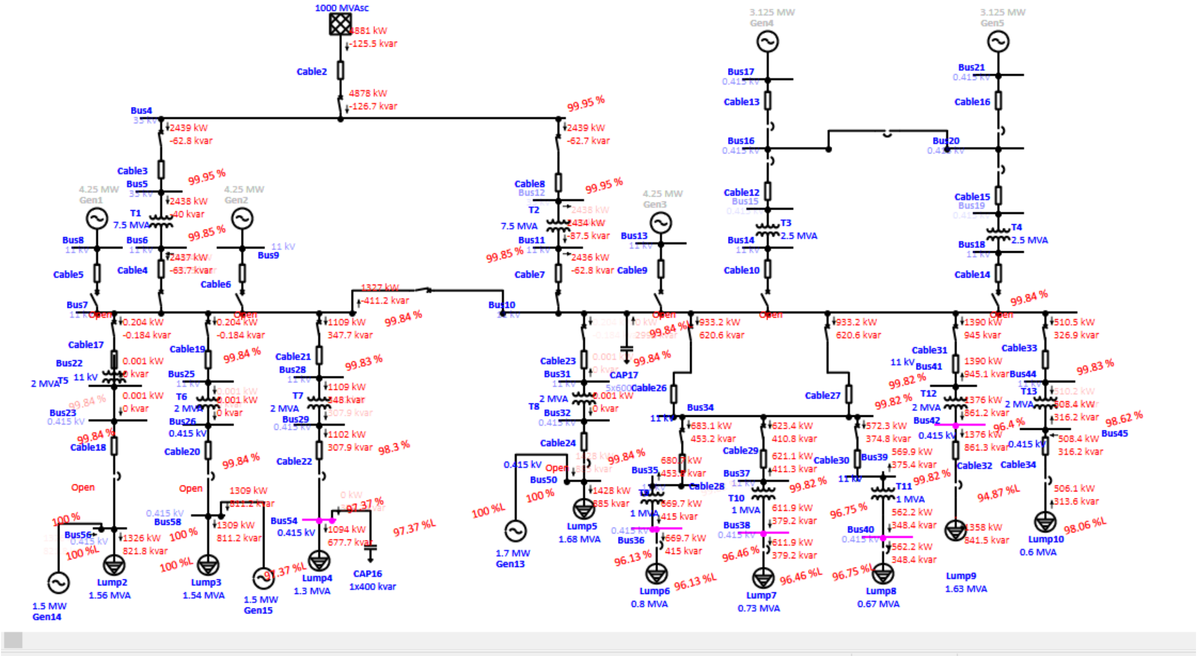

Fig 10: load flow of base case after placing DG and Capacitor simultaneously

II. RESULTS AND DISCUSSION

Base case of the network

Load flow studies were done on the network in figure 3.1 as shown in figure 3.3 to determine the bus voltage magnitude using Newton Raphson load flow technique in ETAP 19.01c.

The obtained values for real power loss and reactive power loss after the load flow of the base case were 238KW and 1093KVAR respectively.

Buses with voltages below 0.95pu are considered as under-voltage violations, while those above 1.05pu are considered as over-voltage violations.

For 11kv buses, acceptable voltage levels range from 10.5kv to 11.5kv, while for 0.415kv buses, the acceptable range is from 0.394kv to 0.436kv.

A summary of buses exceeding these limits is shown in table 1.

Table 1: Simulation results for Bus violation of the base case.

Bus ID	Bus Voltage (pu)	Bus violation type
23	0.94	Undervoltage
26	0.94	Undervoltage
29	0.94	Undervoltage
32	0.93	Undervoltage
36	0.93	Undervoltage
38	0.94	Undervoltage
40	0.94	Undervoltage
42	0.94	Undervoltage
50	0.92	Undervoltage
54	0.92	Undervoltage
56	0.92	Undervoltage
58	0.92	Undervoltage

The voltage profile of bus 23, bus 26, bus 29, bus 32, bus 36, bus 38, bus 40, bus 50, bus 54, bus 56 and bus 58 clearly indicates that the operating voltage falls below the statutory voltage limits of 0.95pu-1.05pu, which is attributed to network overloading, leading to an undervoltage situation.

Results from the cases tested

Case 1: In this case, only capacitor placement was considered. The obtained values for real power loss was 214KW and that of reactive power loss was 924KVAR

In comparison with the base case there was a reduction in both active and reactive power loss which also improved the voltage profile of the network

Below is the simulation result of violated buses after placement of capacitor.

Table 2. Simulation result after capacitor placement

	Base case		Only Capacitor placement	
Bus ID	Bus Voltage (p.u)	Bus Violation Type	Bus Voltage (p.u)	Bus Violation Type
23	0.94	Undervoltage	0.98	Nil
26	0.94	Undervoltage	0.95	Nil
29	0.94	Undervoltage	0.97	Nil
32	0.93	Undervoltage	0.95	Nil
36	0.93	Undervoltage	0.94	Undervoltage
38	0.94	Undervoltage	0.95	Nil
40	0.94	Undervoltage	0.95	Nil
42	0.94	Undervoltage	0.95	Nil
50	0.92	Undervoltage	0.93	Undervoltage
54	0.92	Undervoltage	0.96	Nil
56	0.92	Undervoltage	0.93	Undervoltage
58	0.92	Undervoltage	0.93	Undervoltage

Table 2 clearly shows the impact of only capacitor placement on the base case. The optimal placement of capacitor bank has clearly minimized power loss and improve the voltage profile.

Case 2: This is the case for only DG placement. The obtained values for real and reactive power loss were 60KW and 415KVAR respectively. This result also shows a reduction in power loss when compared with the base case of the network.Below is the simulation result of violated buses after DG placement.

Table 3. Simulation result after DG placement

	Base case		Only DG placement	
Bus ID	Bus Voltage (p.u)	Bus Violation Type	Bus Voltage (p.u)	Bus Violation Type
23	0.94	Undervoltage	0.98	Nil
26	0.94	Undervoltage	0.98	Nil
29	0.94	Undervoltage	0.95	Nil
32	0.93	Undervoltage	0.98	Nil

36	0.93	Undervoltage	0.94	Undervoltage
38	0.94	Undervoltage	0.95	Nil
40	0.94	Undervoltage	0.95	Nil
42	0.94	Undervoltage	0.95	Nil
50	0.92	Undervoltage	1.00	Nil
54	0.92	Undervoltage	0.94	Undervoltage
56	0.92	Undervoltage	1.00	Nil
58	0.92	Undervoltage	1.00	Nil

Table 3 also shows the impact of only DG placement on the base case. The result reveals that optimal placement of DG units has successfully mitigated power loss and hence, improvement in voltage profile.

Case 3: This is the case for the simultaneous placement of DG and capacitor. The values obtained for real and reactive power loss were 92.5KW and 360KVAR respectively.

Below is the simulation result of violated buses after incorporating DG and Capacitor bank simultaneously.

Table 4. Simulation result after incorporating DG and Capacitor bank simultaneously.

	Base case		Incorporating DG and Capacitor simultaneously	
Bus ID	Bus Voltage (p.u)	Bus Violation Type	Bus Voltage (p.u)	Bus Violation Type
23	0.94	Undervoltage	1.00	Nil
26	0.94	Undervoltage	1.00	Nil
29	0.94	Undervoltage	0.98	Nil
32	0.93	Undervoltage	1.00	Nil
36	0.93	Undervoltage	0.96	Nil
38	0.94	Undervoltage	0.96	Nil
40	0.94	Undervoltage	0.96	Nil
42	0.94	Undervoltage	0.96	Nil
50	0.92	Undervoltage	1.00	Nil
54	0.92	Undervoltage	0.97	Nil
56	0.92	Undervoltage	1.00	Nil
58	0.92	Undervoltage	1.00	Nil

Table 4 shows the impact of incorporating DG and capacitor simultaneously on the base case. The data reveals that the simultaneous placement of DG and capacitor has significantly enhanced the active and reactive power performance of the network, indicating a reduction in power loss and overloading issues. From the results obtained, the simultaneous placement of Distributed Generators DG and capacitors shows a better power loss reduction and improvement in voltage profile when compared with their individual placement and the base case.

Below is a voltage profile comparison of the base case to when DG and capacitors are placed simultaneously.

Table 5 gives the simulation result of the violated buses during the different cases considered.

Table 5, simulation result of violated buses during the different cases considered.

	Base case	Case 1: only capacitor placement	Case 2: only DG placement	Case 3: DG and Capacitor Simultaneously
Bus ID	Voltage (p.u)	Voltage (p.u)	Voltage (p.u)	Voltage (p.u)
23	0.94	0.98	0.98	1.00
26	0.94	0.95	0.98	1.00
29	0.94	0.97	0.95	0.98
32	0.93	0.95	0.98	1.00
36	0.93	0.94	0.94	0.96
38	0.94	0.95	0.95	0.96
40	0.94	0.96	0.95	0.96
42	0.94	0.95	0.95	0.97
50	0.92	0.93	1.00	1.00
54	0.92	0.93	0.94	0.97
56	0.92	0.96	1.00	1.00
58	0.92	0.93	1.00	1.00

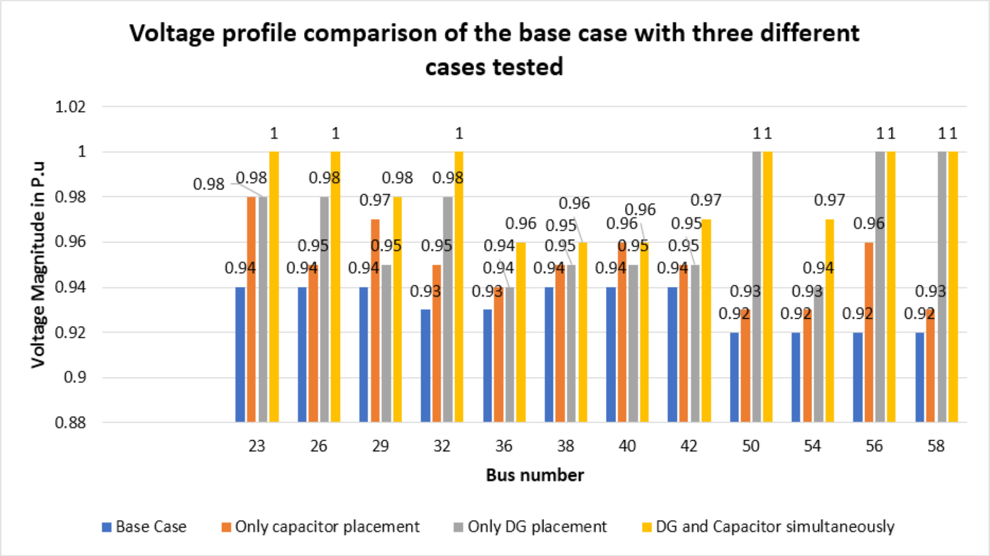

Fig 12: Voltage profile comparison of base case with the different cases considered

Figure 12 shows the voltage profile of the considered network when DG units and capacitors are placed individually and simultaneously in the network. The results obtained reveals that power losses (active and reactive) can effectively be minimized to a considerable extent thereby improving the voltage profile of the network.

The simultaneous placement of DG units and capacitors as considered in case 3 shows that a better power loss reduction and voltage profile improvement can be obtained as compared to their individual placement and the base case of the network.

Impact on power loss

The base case of the network has experienced high power losses with an initial power factor of 0.85pu, with real power loss of 238KW and reactive power loss of 1093KVAR. By implementing full network compensation, DG units and capacitors were optimally placed at critical buses to compensate for the amount of power losses incurred by reactive components in the system. This compensation resulted in an improvement in overall system performance with an improvement in power factor from 0.85pu to 0.96pu, hence minimizing power losses, with real power loss reduced to 92.5KW (61% reduction from the former) and reactive power loss reduced to 360KVAR (78% reduction from the former)

The power loss profile for the compensated state has been compared with that of the uncompensated state (base case) as shown in figure 13

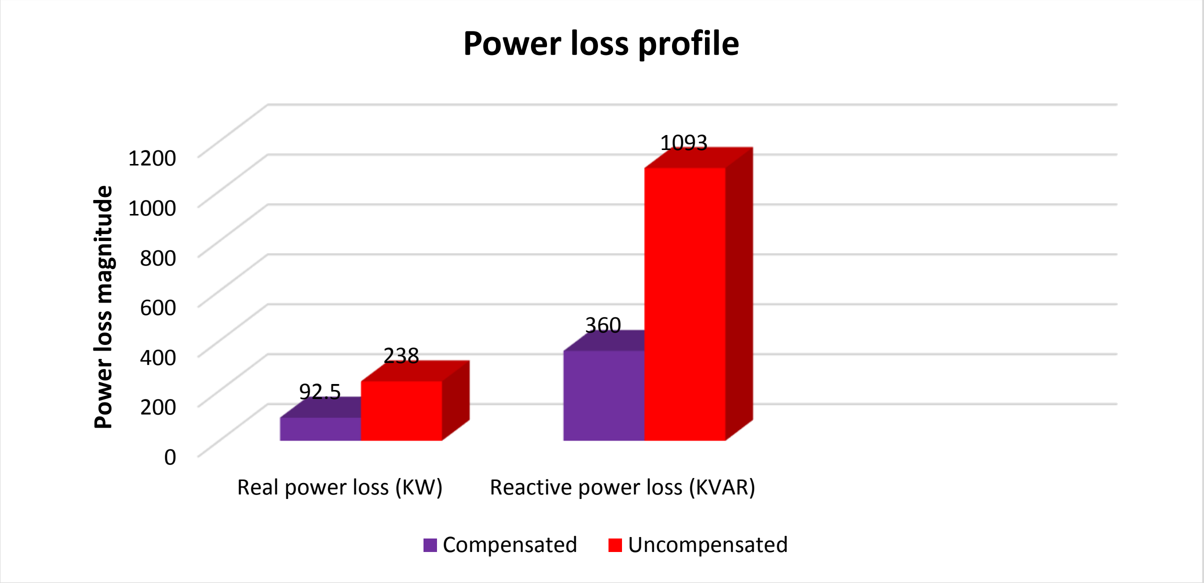

Figure 13: Power loss before and after compensation

III. CONCLUSION

In power distribution network and mini grid, DG units and capacitors are placed to minimize power losses and improve system voltage profile. The placement of DGs and capacitors is complex and tends to introduce greater power losses if not optimally sized and located in the network. This hurdle is overcome with the application of simulation technique for DG and capacitor placement. This technique is applied to the Salvation Ministries Cathedral distribution network. The results obtained shows a significant reduction in power losses and overall improvement of the system voltage profile in comparison with the existing state of the network.

The result also shows that a better power loss reduction is achieved when DG units and capacitor are placed simultaneously than when they are placed individually.

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