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Optimal Placement and Sizing of a Photovoltaic System into Nairobi Distribution Network: Case of Embakasi

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Abstract**—**Kenya is a country with a fast deployment of photovoltaic (PV) systems. The fast deployment of this technology is due to the continuous decrease in the prices of the PV components, the abundance of the solar resource, as well as the measures put in place by the Kenyan government; such as the introduction of the feed-in tariffs to encourage small scale integration of PV systems into the distribution network. The integration of PV systems has proven to be beneficial to the distribution network in terms of reduced power loss, peak shaving, and voltage/frequency support. Nevertheless, if not properly planned can lead to an increase in fault current levels, reverse power flow, feeders' unbalance, and frequency excursion in case of large load loss. This paper deals with the optimal sizing and placement of PV systems into the Nairobi distribution network, with a focus on the Embakasi network section. The objective function of the problem is aimed at minimizing active and reactive power losses and enhance the network's voltage profile. One PV system was optimally sized and placed in the network. The backward-forward sweep (BFS) technique was used for the placement of PV systems and thereafter bacterial foraging optimization algorithm (BFOA) was used for its sizing at the best locations. The optimization problem is solved using MATLAB and then ETAP used to test the optimization results. The results obtained showed the effectiveness of the BFS in finding the best locations for the PV systems and BFOA in finding the best sizes of the PV systems.

Keywords**—**Nairobi, photovoltaic, integration, sizing, placement

V. INTRODUCTION

DESPITE the fact the distribution network was not initially designed to accommodate generating units, the integration of distributed generations (DGs) has seen a tremendous augmentation over the years as the pressure to reduce greenhouse gas (GHG) emissions continues [1]. Distributed Generations which are small and installed closed to load centers have been sorted as an alternative to traditional generating techniques due to the heavy loading and long length of distribution networks [2]. The increasing integration of DGs in the distribution network is healthy to the network as it can lead to reduced power loss, improve network voltage profile, and increase the network reliability in terms of uninterruptible power supply [3][4][3,4]. These benefits can only be achieved if the DGs are properly sized and located. If not so, the DGs could jeopardize the distribution network and this can result in poor power quality [5].

Among all DGs, photovoltaic (PV) is gaining a stronger integration into the distribution network owing to the huge available energy from the sun and the continuous drop in prices of the PV panels [6]. Nevertheless, in the context of Sub-Saharan Africa, the integration of PV systems is still low even though the solar resource on the continent is very large [7]. In Kenya, PV systems both off-grid and on-grid are rapidly multiplying. As of 2019, the installed PV capacity of Kenya stood at 50.25 MWp, with an expected annual growth rate projection of 15% [8]. The increasing integration of PV systems into the Kenyan power systems can be accounted for by the fact that the government has put in place policies such as the feed-in tariff that favours the integration of small-scale PV systems of less than 10MW into the grid [9]. With this, the number of PV systems will continue to proliferate. In case these PV systems are not strategically installed in the distribution network, they could potentially harm the distribution network in terms of voltage deviation beyond limits [10], reverse power flow which can alter the operation of protective devices [11], power factor degradation [12], increase in fault current [13], and total harmonics distortion caused by the PV inverters [14]. Therefore, the systematic panning and sizing of these PV systems are needed in order to minimize the potential adverse effect they can have on the distribution network while maximizing their benefits.

Several techniques have been proposed in the literature for the sizing and placement of DGs/PVs in the distribution network [15]. In [16], the authors proposed the use of a self-organizing hierarchical binary particle swarm optimization with acceleration coefficient to determine the optimal number and sizes of PV systems in a radial distribution network for power loss reduction and voltage profile improvement. In [17], the use of particle swarm optimization (PSO) is proposed to determine the optimal location for PV systems of predetermined sizes in a radial distribution network to minimize power loss and enhance the network voltage profile. The authors in [18], used Binary Particle Swarm Optimization (BPSO) to optimally reconfigure DGs in a radial distribution network with a focus on obtaining the least power loss and enhanced voltage profile in the network. The backward-forward sweep (BFS) load flow calculation method was proposed in [19] for the optimal siting of DGs in the distribution network for loss reduction, with the IEEE 33 node test feeder used as a test network to ascertain the

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performance of the technique. The authors in [20] sequentially used two optimization techniques to integrate multiple DGs in the distribution network. The first approach was the use of PSO to determine the best sizes of the DGs and thereafter loss sensitivity index and weak bus method to find the optimal location of the DGs. The second approach was the use of PSO, GSA, and hybrid PSO-Gravitational Search algorithm for the optimal sizing of the DGs. The use of multileader particle swarm optimization (MLPSO) was used in [21] to find the optimal positions and sized of DGs with the aim of reducing power loss and overcoming the shortcomings of previous optimization algorithms

This paper proposes a two steps optimization method for the placement and sizing of a photovoltaic system in the distribution network for active and reactive power loss reduction and voltage profile improvement. The first step involves the use of the backward-forward sweep (BFS) load flow technique for the optimal allocation of the PV system, and the second step has to do with using the bacterial foraging optimization algorithm (BFOA) to determine the optimal size of the PV system. Embakasi distribution network, which is a section of the Nairobi distribution network is used to validate the effectiveness of the proposed method.

VI. METHODOLOGY

A. Study Network

The Embakasi distribution network, a section of the Nairobi distribution network is used as the case network in this research. The Embakasi distribution network is a 16bus (15 load buses and 1 swing bus) distribution network at a voltage of 66kV as shown in fig. 1. In the load flow simulation of the case network, the load buses are modeled as constant PQ buses, and the simulation is based on June and July 2012 peak load conditions [22]. Load flow analysis of the network is done using ETAP software.

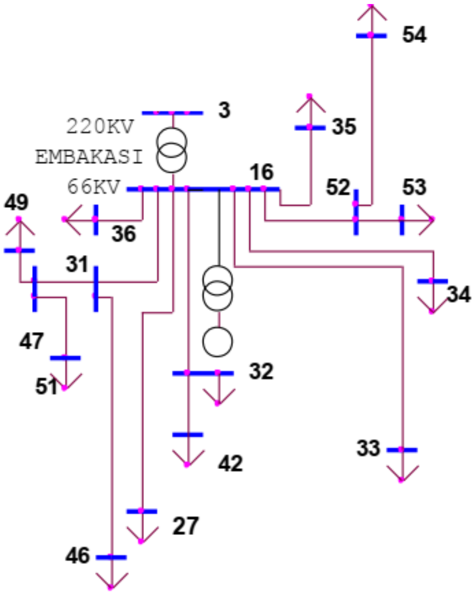

Fig. 1. Embakasi Distribution Network

B. PV Systems Model

The PV system in MATLAB is modeled as a negative PQ loads injective both active and reactive power into the network. It is modeled at a power factor of 0.95 lagging to engulf the capability of the PV voltage source inverters to inject reactive power into the network which is a typical ability of grid-connected PV systems. In ETAP, there is a vast library of PV modules to choose from alongside inputting the appropriate parameters for the voltage source inverter.

C. Problem Formulation

This optimization problem is formulated such that active and reactive power losses are minimized while enhancing the network voltage profile.

a. Objective function

The objective function aims at minimizing the active and reactive power losses in the distribution network. The active power loss $P_{loss(k,k+1)}$ and the reactive power loss $Q_{loss(k,k+1)}$ in the *k-k+1* branch of the network is given by

$$P_{loss(k,k+1)} = \left(\frac{P_{k+1}^2 + Q_{k+1}^2}{|V_{k+1}|^2}\right) * R_{br} \tag{1}$$

$$Q_{loss(k,k+1)} = \left(\frac{Q_{k+1}^2 + Q_{k+1}^2}{|V_{k+1}|^2}\right) * X_{br} \tag{2}$$

Where P_{k+1} is the active power loss at the receiving bus, Q_{k+1} is the reactive power loss at the receiving bus, V_{k+1} is the voltage at the receiving bus, R_{br} and X_{br} are the branch resistance and reactance respectively.
Therefore, the objective function is formulated as

$$f(k) = min \sum_{k=1}^{br} \left[P_{loss(k)} + Q_{loss(k)}\right] \tag{3}$$

Where br denotes the total number of branches.

b. The Constraints

The objective function formulated above is subjected to the following constraints

i. Equality constraints

- Power balance

$$P_G + P_{pv} = \sum_{i=1}^{N_{bus}} P_{load} + \sum_{i=1}^{N_{br}} P_{loss} \tag{4}$$

Where P_G is the active power supplied by the grid, P_{pv} is the active power supplied by the PV system, P_{load} is the active power consumed by the load, N_{bus} is the number of load buses, P_{loss} is the active power loss in the network, and N_{br} is the number of branches that the network has.

$$Q_G + Q_{pv} = \sum_{i=1}^{N_{bus}} Q_{load} + \sum_{i=1}^{N_{br}} Q_{loss} \tag{5}$$

Where Q_G is the reactive power supplied by the grid, Q_{pv} is the reactive power supplied by the PV systems, Q_{load} is the active power consumed by the load, N_{bus} is the number of load buses,

Q_{loss} is the active power loss in the network, and N_{br} is the number of branches that the network has.

ii. Inequality constraints

- Voltage limits

$$V_k^{min} \leq V_k \leq V_k^{max} \tag{6}$$

- Current limits

$$I_{br} \leq I_{br}^{max} \tag{7}$$

- PV Power limits

$$P_{pv}^{min} \leq P_{pv} \leq P_{pv}^{max} \tag{8}$$

D. Optimal Placement and Sizing of the PV system

a. PV placement using backward-forward sweep

The backward-forward sweep (BFS) method of load flow calculation is used to determine the optimal position of the PV systems. This method has been used before to optimally place DGs of predetermined sizes [19]. It has also been used for the placement of capacitors [23].

The BFS technique is used in the first step of this optimization problem to determine the best buses for the placement of the PV systems.

In the forward direction, the BFS technique aims at calculating the drop in voltage at all the buses and update the power and current flow in the network. On the other hand, in the backward direction, the objective is simply to compute the power or the current solutions at the same time updating the voltage at each bus. To illustrate the BFS technique, consider fig. 2.

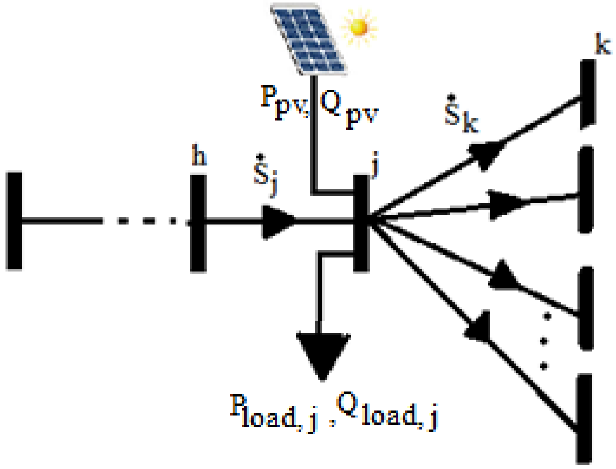

Fig. 2: Radial Network with a PV system

The apparent power $\dot S_j$ at the bus, j is given by

$$\dot S_j = \dot S_{loadj} + \sum_k \dot S_k \tag{9}$$

Where $\dot S_{loadj}$ is the apparent power consumed by the load on bus j, and $\dot S_k$ is the apparent power flowing to bus k.

The current $\dot I_j^{i+1}$ injected into the bus j at iteration $i+1$ is given by

$$\dot I_j^{i+1} = \left(\frac{\dot S_{load,j}}{\dot V_j^i}\right)^* \tag{10}$$

Where $\dot V_j^i$ is the voltage at bus j at the i^{th} iteration

In the backward sweep, the current, $\dot I_{f,j}^{i+1}$ in the f-j branch at iteration i+1 is computed as

$$\dot I_{f,j}^{i+1} = \dot I_j^{i+1} + \sum_k \dot I_{j,k}^{i+1} \tag{11}$$

Where $\dot I_j^{i+1}$ is the current used up by the loads on bus j, and $\dot I_{j,k}^{i+1}$ is the current exiting bus j.

Meanwhile, in the forward sweep, current $I_{f,j}^{i+1}$ is applied to calculate the voltage at bus f as illustrated

$$\dot V_f^{i+1} = \dot V_j^{i+1} - (I_{f,j}^{i+1})(Z_{f,j}) \tag{12}$$

Where $Z_{f,j}$ branch h-j impedance.

The BFS ends when the criterion for convergence for all buses is satisfied. This convergence criterion is

$$\left|\dot V_k^{i+1} - \dot V_k^i\right| \leq \varepsilon \tag{13}$$

ε is the convergence scaler.

At convergence, the j-k branch current equals to $\dot I_{j,k}^{i+1}$ and bus j voltage equals to $\dot V_k^{i+1}$,

b. PV Sizing using Bacterial Foraging optimization algorithm

Bacterial foraging optimization algorithm came into existence in 2002, developed by Pasino, getting inspiration from the "chemotaxis" activity of E. Coli living in the human intestine [24]. E. Coli exhibits their foraging activities in four stages; chemotaxis, swarming, reproduction, and elimination dispersal [25]. This optimization technique is chosen to solve this optimization problem because of its ability to search for new solutions through the process of elimination and dispersal [26].

i. Chemotaxis: It is the process whereby the bacteria swim and tumble by moving the flagella. For a bacterium represented by $\theta^i(j,k,l)$ at j^{th} chemotactic, k^{th} reproductive, and l^{th} elimination-dispersal step, and the chemotactic step size in each run represented by the unit run length parameter $C(i)$, then the chemotactic movement is given by

$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \tag{14}$$

Where: Δ stands for a vector in the random direction with its elements in [-1, 1].

ii. Swarming: During swimming, the bacteria communicate with one another repulsively or attractively, and the signal between them is given by

$$J_{cc}\big(\theta, P(j,k,l)\big) = \textstyle\sum_{i=1}^{S} J_{cc}\left(\theta, \theta^i(j,k,l)\right)$$
$$= \sum_{i=1}^{S}\Big[-d_{attractant}\exp\Big(-w_{attractant}\sum_{m=1}^{P}(\theta_m - \theta_m^i)^2\Big)\Big] + \sum_{i=1}^{S}\Big[h_{repellant}\exp\Big(-w_{repellant}\sum_{m=1}^{P}(\theta_m - \theta_m^i)^2\Big)\Big] \tag{15}$$

Where $J_{cc}\big(\theta, P(j,k,l)\big)$ is the objective function to be minimized, S is the population of the bacteria, p is the number of variables in each bacterium, $\theta = [\theta_1, \theta_2, \ldots, \theta_p]^T$ is a point on the p-dimensional search domain, $d_{attractant}$ is the depth of attractants, $w_{attractant}$ is the width of attractants, $h_{repellant}$ is the height of repulsion and $w_{repellant}$ is the width of repulsion (repellent).

iii. Reproduction: Here, all healthy bacteria split into two while the unhealthy bacteria die, and in so doing the population of the swarm remains constant. Reproduction occurs at N_C Chemotaxis steps and is mathematically given by

$$J^{i}_{health} = \sum_{j}^{N_c+1} J(i,j,k,l) \qquad (16)$$

iv. Elimination and Dispersal: After a certain number of steps of reproduction, N_{re} a sudden event can occur eliminating the bacteria or dispersing them to a new location. All bacterium are subject to an elimination and dispersal probability P_{ed} and in this, some are murdered based on the probability P_e and the rest is dispersed to a new location, and the process restarts. N_{ed} is the number of elimination and dispersal.

The flowchart for the execution of BFOA is shown in fig. 3 below.

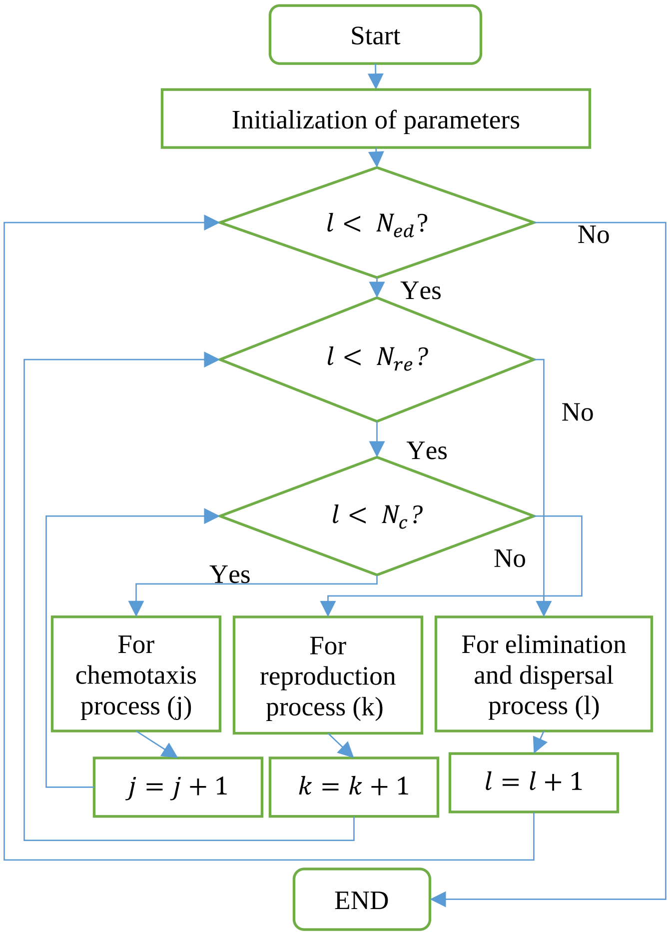

Fig. 3. Bacterial foraging optimization algorithm flowchart

The BFOA parameters used in the simulation is shown in table 1 below.

Table 1. BFOA Simulation Parameters

Parameter	**Symbol**	**value**
Total number of bacteria	S	60
Number of iteration	iter	10
Chemotaxis steps	N_c	25
Swim steps	N_s	4
Reproduction steps	N_{re}	4
Number of elimination-disposal	N_{ed}	2
Elimination-disposal probability	P_{ed}	0.5

VII. RESULTS AND DISCUSSION

The simulation was done using MATLAB to determine the optimal position and size of the PV system. ETAP software was used to validate the results.

A. *Optimal Location and Size of the PV System*

The optimal location for the installation of the PV system as determined by the BFS technique is bus 49 as shown in fig. 5. While the optimal size of the PV system is as determined the BFOA technique is 38282 kW. It is noticed from the load flow of the case network without the PV system that, bus 49 is the bus with the lowest voltage (0.9994pu) alongside bus 51 as depicted in fig. 5. Hence its is chosen as the best bus for the installation of the PV system by the BFS technique.

B. *Network Voltage Profile*

The placement of the PV system on the desired bus leads to an improvement in the voltage profile of the network as shown in fig. 4. Even though the network already has a good voltage profile even before the introduction of the PV system, the introduction of the PV system further ameliorates the voltage profile of the network. Significant ameliorations are noticed on buses 31, 46, 47, 49, and 51, while the bus voltages of the remaining buses remain unchanged.

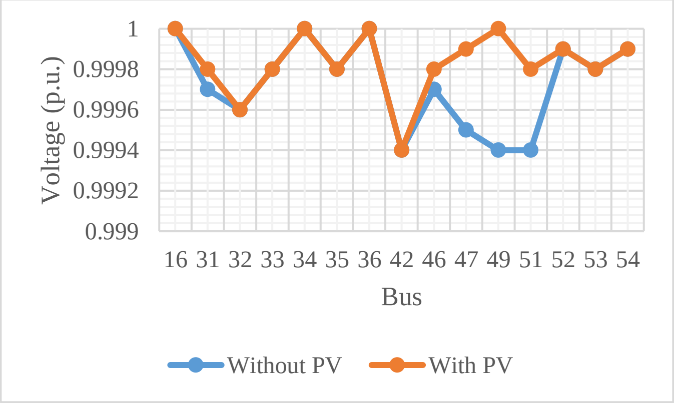

Fig. 4. Network voltage profile with and without the PV system

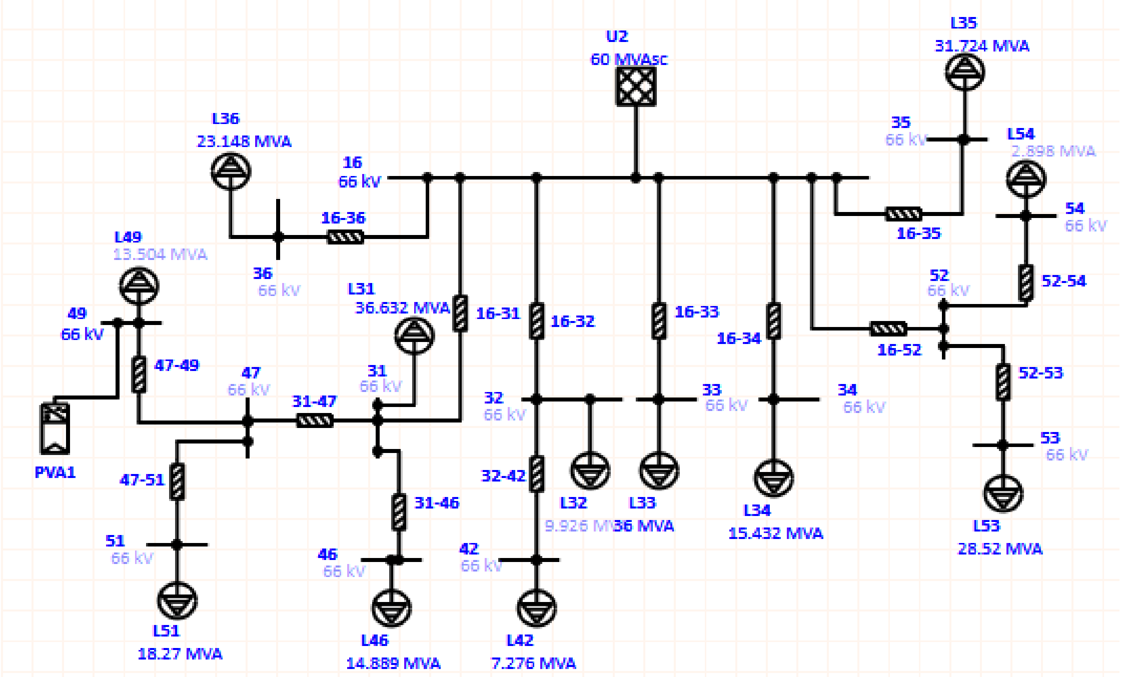

Fig. 5. Test Network with PV optimally placed

C. Active and Reactive Power Loss

The PV system placed at the optimal location significantly aids in decreasing the active and reactive power loss in the network. The most significant reduction in active power loss is noticed in branch16-31 as shown in fig. 5 and 6. It should be noted that branch16-31 is the most heavily loaded branch in the network with bus 31 carrying the largest load of the network (36.632MW). Also, the closeness of bus 49 on which the PV system is installed to the most heavily load bus means the PV system is installed close to the heavy load center of the network, hence, reduced distance. In addition to that, the placement of the PV system on bus 49 results in the grid only supplying the left power needed by the loads on that branch which cannot be provided by the PV system. This results in less stress on the network to meet up with load demands and hence reduction in the network power loss. In all, an overall decrease in active power from 39.9626kW to 36.0796kW as well as an overall reactive power decrease from 62.0123kVar to 35.1733kVar.

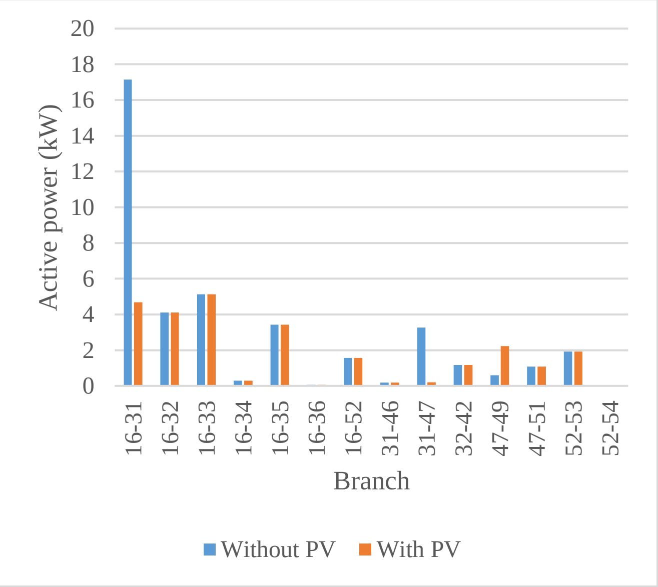

Fig. 5. Active power loss with and without the PV system

IV. CONCLUSION

This paper dealt with the optimal placement of a PV system in the Embakasi distribution network. The backward-forward sweep method of load flow calculation was used to determine the optimum location of the PV system while the bacterial foraging optimization algorithm was used to determine the optimum size of the PV system. The optimization problem was formulated as a minimization problem minimizing power loss while enhancing the voltage profile of the network. The optimization problem was solved using MATLAB and then ETAP was used to test the optimization results. Simulation results demonstrated the effectiveness of the method in finding the best bus to install the PV system as well as the appropriate size of the PV system. This solution could be used by the distribution network operator to plan the installation of a centralized PV system in the Embakasi areal distribution network for network voltage improvement and power loss reduction.

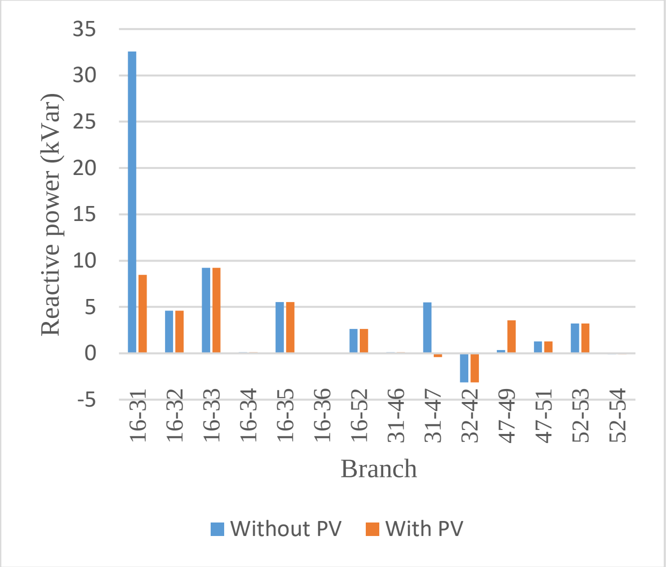

Fig. 6. Reactive power loss with and without PV system

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