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Loss minimization and voltage profile enhancement of distribution system with the integration of renewable distributed generation and capacitor

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The continuation of load demand increment in the distribution system and its consequences on the voltage deviation and distribution system loss have a negative impact on system quality. Distributed generation (DG) and capacitor bank can be considered the most suitable enhancement devices for these problems if they are allocated appropriately in the distribution system. In this paper, the impacts of renewable DG and capacitor bank on power loss and voltage profile of Adama real distribution substation in Ethiopia with four scenarios of DG and capacitor interconnection are investigated. In each scenario, the performances of interconnected DG and capacitor in terms of voltage and power losses are analyzed through simulation in Electrical Transient Analyzer Program (ETAP).Voltage sensitivity index (VSI) and genetic algorithm (GA) implemented in ETAP software is utilized to determine the optimal location and sizing of DG and capacitors. Results showed that a substantial reduction in active power losses and voltage profile improvement is achieved with a combination of DG and capacitor bank compared to DG and capacitor separately. The reduction of active power loss percentage is reached to 52%.The cost that is associated with power loss is minimized by 51.7 %. Also it was found that based on the time taken for the analysis, GA technique implemented in ETAP is slightly effective than VSI variational algorithm methods for capacitor sizing.

Keywords: Distributed Generation, Optimal capacitor placement, Power loss minimization, Voltage profile improvement, Voltage sensitivity index

1. Introduction

In the structure of electric power system, distribution network represents the final connection between high-voltage transmission systems and low-voltage consumers. Due to high R/X ratio of distribution network, a higher power loss is observed in distribution system compared to transmission network [1–3]. Especially in many developing countries like Ethiopia, the technical and commercial losses of transmission and distribution system is very highdue to low system management and poor revenue collection respectively. According to some reports (e.g. [4,5], the electricity transmission and distribution losses in Ethiopia reaches 20%. This is very high compared to the world average ranges of 10% to 13% [4,6]. Therefore, in order to improve the efficiency of the distribution system, these losses need to be limited.

Various alternatives have been done to decrease the losses in distribution networks. Capacitor placement, distributed generation (DG), and network reconfiguration are the

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most common options used to enhance distribution system voltage profile and power losses [7,8]. In the last few years, renewable DG placement has become a very renowned research area. After incorporating DG into a system, it provides several benefits such as voltage profile enhancement, reduction of power loss and improve system stability [9,10]. Combination of DG and capacitor bank can play important role for reducing power loss and enhancement of voltage profile [11,12].

Ethiopia is blessed with immense renewable DG potential like solar energy, and has annual total solar energy reserve of 2.199 million TWh/annum [13,14]. To improve the utility performance, the government of Ethiopia has also a target to reach a share of 16 % of its energy supply from solar energy resources by 2025 from inexistent share of solar PV power [15,16]. Accordingly, the Ethiopian government as well as other key stockholders in the energy sector is motivating the exploration of renewable distributed generation technologies. To achieve the placed goal of country, analyzing the impact of renewable DG with the combination of capacitor bank on the distribution system for minimizing loss could be one of the viable options. Such kind of analysis is not only offering enhancement of distribution system performance, it also provides environmental benefits [17,18].

For the past few years, many researchers have studied the impact of DG on the distribution system performances with different sizing and placement optimization techniques, and recently some of the researchers also analyzed the impact of simultaneously incorporating DG and shunt capacitoron the distribution system.

The impact of DG on the power loss and voltage profile of conventional distribution system has been studied in [19–27] In Refs.[28,29] enhancement of distribution line loss and voltage stability with integration of DG have been studied. Manas et al.[30] explored the impact of DG integration on the power loss and voltage profile improvement of distribution network under the real case study of Tezpur University, India. Ud et al.[31] have proposed optimal integration of DG and reconfiguration of the radial network to minimize line losses, total harmonic distortion (THD), and to improve the voltage profile of the system. In [32], the optimal reconfiguration of distribution systems is addressed to enhance reliability and minimize power losses of distribution networks.Siahbalaee et al. [33] proposed a network reconfiguration methodology with the presence of DG to achieve power loss minimization and voltage profile improvement.

Das et al.[34] explored the optimal integration of DG and shunt capacitors on distribution network to minimize the annual energy losses along with real power loss reduction and improvement of voltage profile.Saleh et al.[35] have presented the optimal allocation of DG and capacitor bank on the conventional distribution system to minimize power loss and voltage deviation. The impact of DG and capacitor bank on the power loss, voltage profile and stability of distribution network has been explored in [36]. In Refs.[37,38] the impact of optimal capacitor placement on the power loss and voltage magnitude of distribution network is presented.

Different optimization techniques, such as metaheuristic approach [19–24][31,33,35–37] epsilon constrained (EPC) and min-max fuzzy satisfying (MMFF) technique [32], multiphase optimal power flow and a genetic algorithm [38], analytical approach [25–29,34], analytical and fuzzy [30] have been used to solve the optimization problems for DG, capacitor siting, sizing and network reconfiguration.

From the aforementioned works, the issues of DG influence on the performance of distribution system with different optimal location and sizing techniques have been observed. The impact of capacitor placement and network reconfiguration on the power loss of distribution system is also reviewed. However, the comparative analysis studies on the economic and technical impact of renewable DG and capacitor togetherfor the real case study of distribution system is not explored highly. Examining the techno-economic impact of renewable DG integration on the real distribution network for specific location can highly serve the specific utility owner for selecting the best compensation devices for their network, and the concerned stakeholders also benefited from the analysis to obligate the utility owner in order to fulfill the distribution system power quality standards. To the author's knowledge, most of the existing work on optimal siting and sizing of DGs in distribution systems considers IEEE test bus for analysis. However, in real time scenario identifying the best location and size for DG and for other compensation devices may not be easy because of various real time constraints.Therefore, this research aimed to reduce this gap by examining the impact of simultaneous renewable DG and capacitor bank integration for the power loss and voltage profile improvement of distribution network under the real case study of Adama distribution network, Ethiopia. The various costs such as DG capital, capacitor installation, DG operation and maintenance (O&M), cost that is associated with power losses are examined for various DG and capacitor integration scenarios at the specified load of the location.

As stated in our investigation [39], the location is well endowed with solar energy potential with annual average radiation of 6.2 kWh/m^2/day, and in another way, the overall installation cost of solar PV is anticipated to decrease considerably in the near term throughout the globe. The average cost of PV will be 589$/kW by 2030 and 320 $/kW by 2050 against the average of 1110$/kW in 2018 [40,41]. Due to this, solar PV is considered as renewable DG in this analysis.

The optimal location and sizing of DG and capacitor is ascertained by voltage sensitivity index (VSI) approach. For comparison purpose, the capacitor placement problem is also solved using genetic algorithm (GA) implemented in the ETAP software, which was not explored in another literature in depth.

The rest of the paper is organized as follows: Methodology of the study, which describes about power flow analysis, objective function, sizing method and tested system are presented in section 2. Simulation results and discussions are provided in section 3. Finally, the conclusion of this investigation are provided in section 4.

2. Methodology

2.1 Power flow equations

To observe the impact of DG and capacitor on the considered or for any distribution network, power flow analysis is important**.** Consider a branch connected between buses i and j of a radial distribution network as shown in Fig. 1. The real and reactive power flow through the branch and receiving end bus voltage by neglecting shunt conductance and susceptanceare evaluated using Eqs. (1)– (3) [42][43].

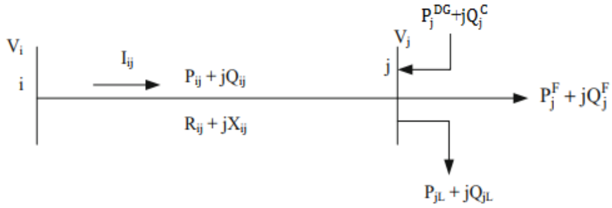

Fig. 1. Model of a branch connected between buses i and j

$$P_{ij} = P_j^F + P_{jL} - P_j^{DG} + \frac{R_{ij}}{V_i^2}(P_{ij}^2 + Q_{ij}^2) \quad (1)$$

$$Q_{ij} = Q_j^F + Q_{jL} - Q_j^C + \frac{X_{ij}}{V_i^2}(P_{ij}^2 + Q_{ij}^2) \quad (2)$$

$$V_j^2 = V_i^2 - 2(P_{ij} R_{ij} + Q_{ij} X_{ij}) + \frac{R_{ij}^2 + X_{ij}^2}{V_i^2}(P_{ij}^2 + Q_{ij}^2) \quad (3)$$

WhereP_{ij} and Q_{ij} is active and reactive power flow between *i* and *j* bus, $P_j^F$and Q_j^F is active and reactive power flow behind bus j, P_{jL} and Q_{jL} is active and reactive load of j^{th} bus, $R_{ij}$and X_{ij} is branch resistance and reactance between i^{th} and j^{th} bus,V_i and V_j is voltage magnitude at bus i and j,P_j^{DG} and $Q_j^C$is the active power injections by DG and the reactive power injection by capacitor at bus j

The flow of current across branch *ij*is evaluated using:

$$I_{ij} = \sqrt{\frac{P_{ij}^2 + Q_{ij}^2}{V_i^2}} \quad (4)$$

Where I_{ij} is the flow of current across ij branch

The real and reactive power loss in the line section between buses i and j is calculated by using the following equation:

$$P_{Loss(i,j)} = I_{ij}^2 R_{ij} \quad (5)$$

$$Q_{Loss(i,j)} = I_{ij}^2 X_{ij} \quad (6)$$

The total real and reactive power loss of the system can be determined by summing of all the branch power loss and it is expressed in Eq. (7).

$$P_{T\,Loss} = \sum_{i=1}^{nb} P_{Loss}(i,j) \quad (7)$$

Where $P_{T\,Loss}$ is the total power loss of the system and nb is total number of the branches

2.2. Objective function

The objective of the proposed study is to minimize the power loss of the distribution system and voltage deviation (V_D) at the average load of the distribution system. The mathematical formulation of the objective function is given by

Minimize (F) =min ($P_{TLoss} + V_D$) (8)

Where voltage deviation (V_D) of each bus can be defined as[9]:

$$V_D = \sum_{i=1}^{n} \frac{|V_i^{ref} - V_i|}{V_i^{ref}} \quad (9)$$

Where, V_i is the voltage in p.u. at i^{th} bus of the system, V_i^{ref} is the nominal substation voltage (1.00 p.u.) and n is number of bus.In a power system, it is desirable to maintain the load bus voltages within specified deviation limits usually within ±5% of the nominal substation value (1 p.u). In this study also ±5 deviation from the nominal voltage is maintained.For an ideal DG and capacitor interconnection, the deviation value should decrease with DG and capacitor placement.The constraints subjected to the set of equality and inequality constraints can be given as:

- Equality constraints

The active and reactive power flow in all branches of the system must satisfy Eqs. (1) and (2).

- Inequality constraints

The voltage magnitude of each bus must lie between minimum and maximum range and it is expressed as:

$$V_i^{min} \leq V_i \leq V_i^{max} \qquad i \in n \quad (10)$$

Where V_i^{min} minimum voltage of i^{th} bus (p.u), V_i^{max} is maximum voltage of i^{th} bus (p.u) and n is total number of buses.

The total compensation provided by the shunt capacitors should not be greater than total reactive load of a network.

$$\sum_{j=1}^{ncap} Q_j^C \leq \text{Total Q} \qquad (11)$$

Where $ncap$ is total number of capacitor

It is assumed that, DG can penetrate up to its optimal sizes.

2.3 Location and sizing issues

Inappropriate location and size of DG and capacitors in the network can results greater system losses, voltage deviation and system instability [44][34]. Therefore, optimal placement and sizing of DG and capacitors are required to achieve the proposed objectives. In this study, voltage sensitivity index (VSI) method is used to find the optimal location of DG and capacitor.Voltage sensitivity index is a numerical technique that finds the most sensitive node of the system from voltage sensitivity point of view. This could be done by injecting DG with 25% of the total feeder loading capacity at each node at a time and computing the voltage index by using Eq. (12) [45][46]. Then the node with least voltage sensitive index has been selected as best location for the placement. After identifying the optimal location, variational algorithm is used to find the optimal DG size.

$$VSI_i = \sqrt{\frac{\sum_{k=1}^{n}(1 - V_k)^2}{n}} \qquad (12)$$

Where V_k is voltage at k^{th} node .

The algorithm for optimal size and location of DG into radial distribution network that can be achieved using the VSI in ETAP software is described in the following steps:
Step 1: Run the base case load flow
Step 2:by penetrating the DG of size,25% of the total feeder load at each node (except at source node); calculate the VSI at the respective bus.
Step 3: Select the bus with lowest value of voltage index as the optimal location for placing the DG.
Step 4: At optimal location, vary the DG size in small steps and calculate the total power losses at each step by running load flow.
Step 5: Take the DG size that results a minimum losses as optimal.
Step 6: Repeat step 4 to step 5 for all optimal buses in the priority list.
Step 7: Stop.

Thesame stepis followed to size the capacitor bank at the specified location.

2.3.1. Capacitor placement computational methods in ETAP by GA implementation

ETAP is a fully graphical electrical power system analysis program, and uses the GA for optimal capacitor placement (OCP).Genetic algorithms belong to the larger class of evolutionary algorithms (EA), which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, selection, crossover andmutation. Even though GA is probabilistic, it is not strictly random search. It is established on selection of the nature, best survival rule and depends upon the population of possible solutions in its iteration. Fig.2 presents the flow chart of a typical GA that is used in the simulation.

The optimal capacitor placement toolbox in the ETAP requires an objective function and the encoding techniques to enhance voltage profile, improve the power factor and minimize the system power losses. The objective of OCP is to minimize the cost of the system. These costs includes; fixed capacitor installation cost, capacitor purchase cost, capacitor bank operating cost and cost of real power losses [47]. The cost function can be represented mathematically as:

Min Objective Function

$$= \sum_{k=1}^{Nbus} (\mathrm{x_k C_{ok} + Q_{ci} C_{1k} + B_k C_{2k} T}) + \mathrm{C_2} \sum_{k=1}^{Nload} (\mathrm{T_1\, P}_L^1) \qquad (13)$$

Where $Nbus$ is number of bus candidates, $\mathrm{x_k}$ is 0/1, 0 means no capacitor installed in bus 1,$\mathrm{C_{ok}}$ is installation cost,$\mathrm{C_{1k}}$ is Per kVar cost of capacitor bank,$\mathrm{Q_{ck}}$is capacitor bank size in kVar,$\mathrm{B_k}$ is number of capacitor bank, $\mathrm{C_{2k}}$ is operating cost per bank per year, T is planning period (Year), $\mathrm{C_2}$ is cost of each kWh loss, $Nload$ is load levels (maximum, minimum, and average), $\mathrm{T_1}$ is time duration of load level l, P_L^1 is total system loss at load level l.The main constraints should agree with stated power flow constraints. Also all bus voltage magnitudes have to be within the upper and lower limits.

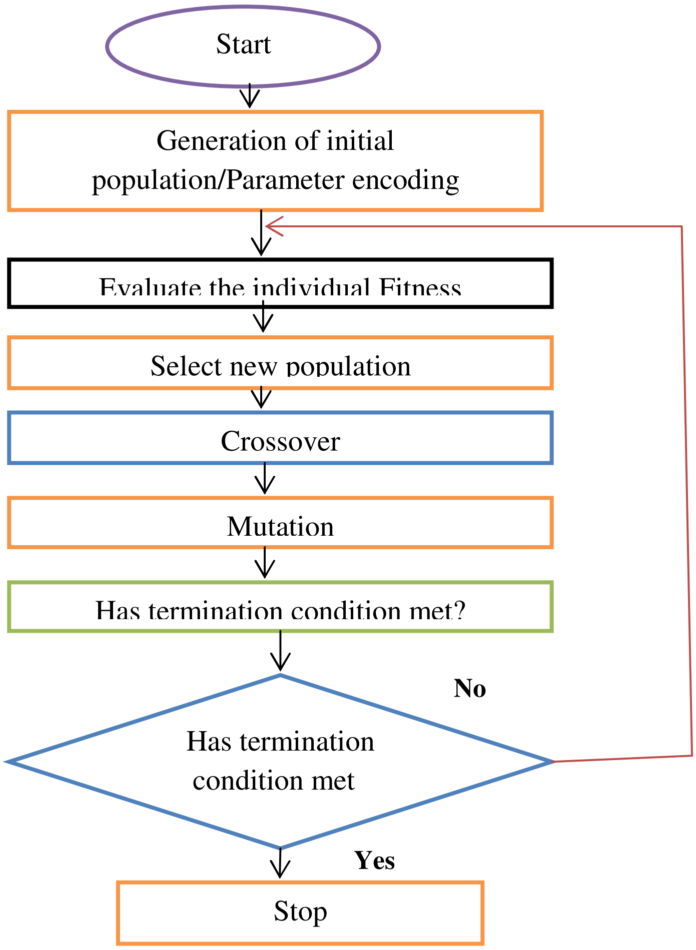

Fig .2. Flowchart of GA optimization algorithm.

2.4. The test systemand cost estimation

The prospect of DG and capacitor placement is investigated by selecting a practical distribution substation of Adama city in Ethiopia. Currently, Adamasubstation is supplied from the Kokapower plant and Adama wind farm with 132kV transmission line stretched into the substation. The distribution system in the substation has a 15kV line system with eleven feeders such as L1, L2, L3, L4, L5, M1,M2,M3,M4,M5 and M6. A general one-line diagram of the 132/15 kV with the specified eleven feedersand total load is shown in Fig.3.The overall technical information of the network data has been also shown in Table 1. Before and after the integration of DG and capacitor, adaptive Newton-Raphson method for system load flow analysisis used in ETAP environment.

To analyze the viability of the proposed system, commercial information of DG, capacitors and cost of energy is needed. Theoverall cost information for DG and capacitors have been specified in Table 2. Based on the electric tariff of the country, the total cost of power loss of distribution network for the specified period is evaluated using Eq. (14)[48].

$$C_{Loss} = E_C * P_{T\,Loss} * T \qquad (14)$$

Where C_{Loss} cost of power loss ($),$E_C$ is energy cost ($/kWh) and T is time (8760 hours).

Inthe above equation(13)analysis, 0.04 $/kWh energy cost is considered for the existing loss, and by considering the 2021 country plan on electricity tariff incremental, 0.07 $/kWh is considered to analyze the loss cost for the loss starting from 2021 [49].

The approximate net saving due to DG and capacitor integration is formulated as the difference between the energy cost before and after DG and capacitor integration by considering the DG and capacitorinvestment cost is calculated as:

$$S_{Net.sav} = (E_C T\,(P_{T\,loss}^{before} - P_{T\,Loss}^{after}) + (E_{(kWh)} * E_C)) - DG_{tot.inv} \qquad (15)$$

Where $S_{Net.sav}$ is total net saving ($/year), $P_{T\,loss}^{before}$ total system loss before DG integration (kW), $P_{T\,Loss}^{after}$ total system loss after DG placement (kW),$E_{(kWh)}$ is the annual solar PV energy output in kWh, and $DG_{tot.inv}$ is total DG investment cost ($).The annual solar PV energy output in kWhis given by Eq. (16) below.

$$E_{(kWh)} = P_{Tot\,.inj} * 24 * 365 * CF \qquad (16)$$

Where $P_{Tot\,.inj}$is the total power injected to grid [kW], and CF is the capacity factor. In the solar PV potential analysis investigation of the location, the capacity factor (CF) of the site is estimated as 0.2 or 20% [39], and given by Eq.17[50].

$$CF = \frac{E_{PV}\ \ (kWh/year)}{PV_{rated}\ \ * 24 * 365} \qquad (17)$$

Where E_{PV} is the annual energy output in kWh and PV_{rated} is the rated PV power in kW , and in this case, it is the total power injected to the grid. Therefore, to analyze the annual solar PV energy output of the designed system, 0.2 $CF$is considered in this investigation.

$$S_{Net.sav} = E_C T\,(P_{T\,loss}^{before} - P_{T\,Loss}^{after}) - C_{total\,inv} \qquad (18)$$

Where $P_{T\,loss}^{before}$totals system loss before capacitor integration (kW), $P_{T\,Loss}^{after}$ total system loss after capacitor placement (kW), and $C_{total\,inv}$ is total capacitor investment cost ($).

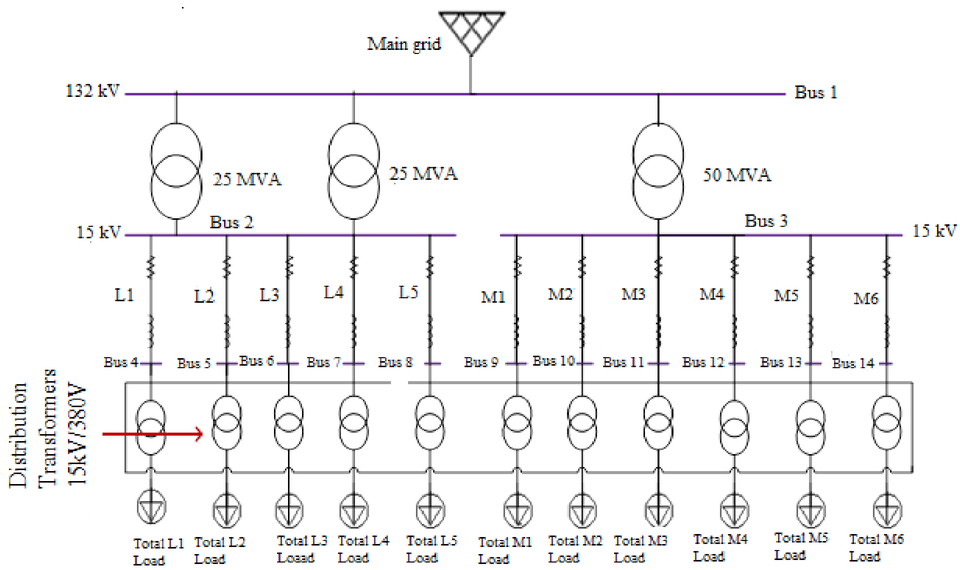

Fig. 3.Single line diagram of Adama distribution substation.

Table 1: Line parameters and load data of the substation.

Feeder name	Average estimated line length in km.	Total MVA of distribution Transformer	Average load (MW)	Resistance in (Ohm)	Reactance in (Ohm)
L1	9.8	23.32	5.6	1.47	0.98
L2	12	25.27	6.2	8.12	1.38
L3	10.5	14.57	5.5	1.57	1.05
L4	3	17.23	4.5	0.45	0.31
L5	6.5	23.88	4.5	4.55	0.78
M1	8.9	24.72	7	6.23	1.06
M2	5	23.42	2.75	3.50	0.60
M3	9.9	21.73	6.6	1.48	1.00
M4	4	19.98	6.6	0..62	0.41
M5	20	13.45	3	10.0	2.21
M6	16.6	22.28	2.75	2.49	1.66

Table 2: Cost data of DG for solar PV and Capacitor

DG for solar PV		Capacitor	
Parameter	**Specification**	**Parameter**	**Specification**
PV capital cost with convertor	1400 $/kW)	Purchase cost	15 $/kVAr for 200kVAr
Operation cost	12 $//kW/year	Operation cost	1$/ kVAr /Year
Life time	25years	Installation cost	7 % of purchase price
		Life time	10 years

3.Simulation results and discussion

As it is mentioned in the above, in this study, the technical and economic impact of renewable DG and capacitor bank on the distribution network has been analyzed. Voltage profile and network loss of the distribution system is properly analyzed as technical parameters before and after insertion of the compensation devices. With the proposed algorithm, optimum size and location of DG and capacitors were obtained by running load flow analysis in ETAP software on a real 14-bus distribution substation of Adama city in Ethiopia. In addition, for checking the validity of the proposed approach, the numerical outputs are also compared to other techniques that are available in the different published literature. In the simulation result, DG power factor is set at unity.To analyze the impact of DG and shunt capacitors properly the following four cases are considered. In each cases, various costs have been calculated which includes loss cost ($/year), total DG and capacitor investment cost ($) and saving from power loss ($/year).

Case 1: Base case (without connecting any enhancement device)
Case-2: Only DG is placed at the optimal locations.
Case-3: Only capacitor is placed at the optimal locations
Case-4: Both DG and capacitor are placed simultaneously.

Case 1: For comparison purpose, the performance of the distribution system at the base case has been simulated without connecting DG and capacitor. From the simulation result 3,109 kW total power loss in the system, which is equal to 27.234MWh/year were observed. The total cost of power loss was 1,089,393 ($/year). The per unit voltage profile of each bus is indicated in Fig.4, and average voltage profile from 0.892 p.u to 1p.u was observed.

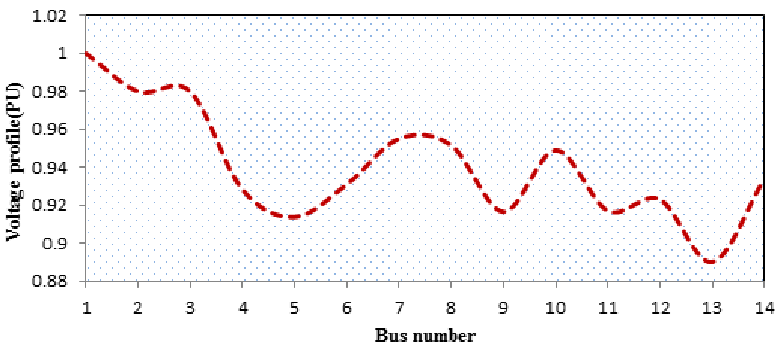

Fig.4. Base case voltage profile of the test system.

To select the optimal placement of DG and capacitor, medium voltage bus for 15KV feeder system is considered. Based on VSI algorithm, bus 5 bus9 and bus13 were selected as optimal locations for DG, andbus 4, bus 5, bus 6, bus 9,bus 12 and bus13 for capacitor placement. The following cases are also simulated and analyzed with the consideration of these optimal locations.

Case 2: Only renewable DG (solar PV)is placed at the optimal locations. The optimal sizes of DG on the respective locations are 4.1MW, 4.8 MW, and 2.8MW. In this case, the total real power loss is reduced from 3,109to 1,786 kW after DG placement and loss reduction is 43 %. 463,579$/year are saved from power loss after DG placement.

Case 3: Only capacitor is placed at bus 4, bus 5, bus 6, bus 9, bus 12 and bus 13 with 3MVAr, 4MVAr, 3MVAr, 4MVAr, 3.2MVAr, and 2MVAR respectively. The total real power loss is reduced from 3,109 to 2,390.7 kW. 279,969$/year are saved from power loss after capacitor placement.

Case 4: Combined DG and capacitor were placed at the optimal locations. The total optimal size of DG and capacitor selected were 4.1 MW and 2.8 MVAr at bus 5, 3MVAr at bus6, 4.8 MW and 3.8 MVAr at bus 9, and 2.3 MW and 1.8MVAr at bus 13 respectively. The total real power loss is deduced from 3,109 to 1,521 kW. 556,435.2 $/year were saved from power loss after DG and capacitor placement.

Table 3 compares the results of different cases considered. It is seen from the table that if optimal size of DG at bus 5, 9 and 13, and the capacitor at bus 5, 6, 9 and13 were placed simultaneously, more loss reduction can be achieved compared to the other cases considered.

Table 3: Simulation results for all cases of distribution system.

Particulars	Case 1	Case 2	Case 3	Case 4
Total kW loss	3,109	1,786	2,310	1,521
% Loss reduction	0	43	25.7	52
Loss cost ($/year)	1,089,393	625,814	809,424	532,958
DG Location and Size (MW)	-	5 (4.1),9 (4.8), 13 (2.8)	-	5 (4.1),9 (4.8), 13 (2.3)
Capacitor Location and Size (MVAr)	-	-	4(3),5(4),6(3),9 (4),12(3.2), 13(2)	5(2.8), 6(3), 9(3.8), 1.8(13)
Total DG investment cost ($)	-	25,740,000	-	24,640,000
Total capacitor investment cost ($)	-	-	500,160	296,970
Saving from power loss ($/year)	-	463,579	279,969	556,435
$\mathbf{V_i^{min}}$ (p.u.)	0.892	0.954	0.951	0.958
Accumulative Profit during DG and capacitor lifetime ($)	-	7,657,018	2,299,530	8,461,844

Voltage profile

The comparisons of voltage profile at different buses for all considered cases in the distribution network are shown in Fig.5. It can be seen from the figure that, case 4 indicates better voltage level among other cases and the average system voltage profile gets improved from minimum 0.958p.u up to 0.99 p.u. Also, by considering only the bus which is load is connected (starting from bus 4),the results of voltage deviation indicates that, the minimum deviation of distribution system was improved from the base value of 0.0485 to 0.034, 0.028,and 0.022 for case 2 to 4 respectively as shown in Fig.6.

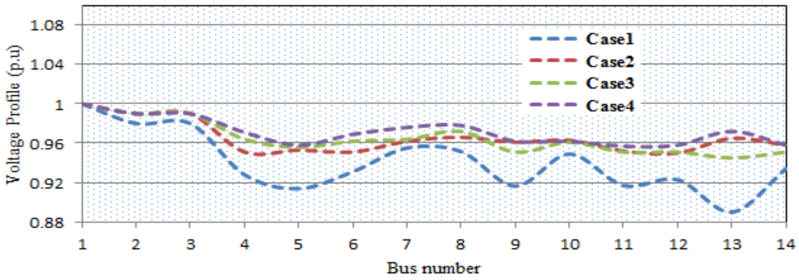

Fig. 5. Voltage profile comparison of all cases of distribution system.

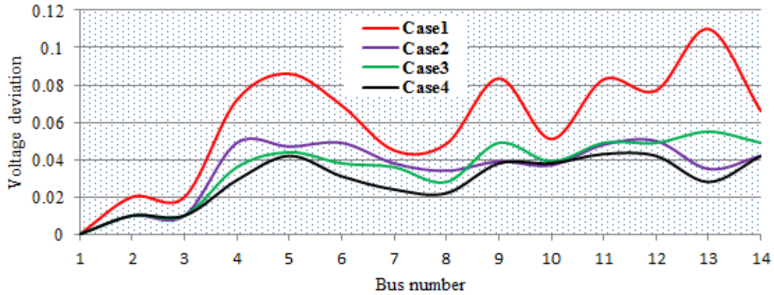

Fig.6.Comparison of voltage deviation at each bus for four cases.

3.1. Comparisonof sensitivity analysis and OCPtoolbox in ETAP for capacitor sizing

With VSI algorithm, repeated power flow is conducted for sizing the capacitor until the minimum loss point is achieved. This is somewhat how time taker.

In the OCP problem with ETAP, first the distribution network load flow at the base case is simulated. The buses that cross the boundaries of the voltage constraints are nominated for the capacitor placement. Then optimal size is done by using GA technique implemented in ETAP software with the system cost minimization objective function. Range of capacitor bank size, purchase and operating cost of the capacitor are given as input to the OCP toolbox. As shown in Table 4, GA technique implemented in ETAP is effective than the numerical VSI variational algorithm methods, and technique takes minimum time to get the optimal placement and size of the capacitor in the network.

Table 4: Simulation results comparison using VSI and GA

Particulars	VSI	GA in ETAP
Total kW loss	2327	2310
% Loss reduction	25.2	25.7
Capacitor location and size (MVAr)	4(3.4),5(3.6),6(2.7),9 (4),12(3), 13(1.8)	4(3),5(4.1),6(3),9 (4.01),12(3.2), 13(2)
V_i^{min} (p.u.)	0.951	0.953
Approx. analysistime (Min)	75	10

For checking the validity of the proposed method, the simulated outputs are also compared to other techniques that are available in the published literature as shown in Table 5. From the numericaloutput we deduced that the proposed methodology for optimal placement and sizing of DG and capacitor were affirmed competitive in comparison with other metaheuristic and analytical approach in terms of minimizing the losses and voltage profile improvement. Because in real time scenario identification of best location and size for DG may not be easy because of various real time constraints like time varying loads.

Table 5: Simulation results comparison for 14-bus distribution network.

Particulars	Particle swarm optimization [51]	Analytical load flow [27]	GA [52]	VSI&OCP
% Loss reduction	58.7	32.5	59	52
DG location(s) & Sizes (MW)	4(70),5(62),7 (19)	7 (115)	3(149),9(52),13(14)	5 (4.1),9 (4.8), 13 (2.3)
Capacitor location and size (MVAr)	4(0.05),5(8.1)9(19),10 (7.5),11 (0.6), 13 (7.75),14(6.3)	-	-	5(2.8), 6(3), 9(3.8), 1.8(13)
Maximum % of optimized voltage	7 %	9%	5%	8%

4. Conclusion

This paper has presented the effect of integration of renewable DG and capacitor bank on a real part of Ethiopian distribution system at Adama city for improvement in the voltage profile and loss reduction. Voltage sensitivity index and genetic algorithm implemented in ETAP softwarehas been used for optimal size and location of DG and shunt capacitors. The distribution system parameters were analyzed by incorporating optimal size of DG and Capacitor bank at the specified locations. Based on the simulation results, it is observed that:

- ✓ Optimal allocation of renewable DG reduces the power losses and improves the system voltage profile.
- ✓ Voltage profile is improved with capacitor placement alone but the loss is not reduced significantly.
- ✓ When the DG is combined with the capacitor bank and is optimally placed, a substantial minimization of real power loss and improved voltage profile is achieved.
- ✓ Cost saving maximization has been achieved distinctly.
- ✓ By considering the time taken for the analysis, GA technique implemented in ETAP is slightly effective than VSI variational algorithm methods for capacitor sizing. In other way, the suggested methodology in the studywas confirmed, as it is competitive in comparison with other metaheuristic and analytical approach.
- ✓ The proposed methodology is capable for solving this problem onother higher practical distribution test systems to minimize the real power loss, which leads to reduction in total annual cost and voltage deviation.

It can be concluded from the results that, the Ethiopian electric utilities should encourage the combined integration of this DG and capacitor into Adama city, Ethiopia distribution systems as an alternative to improve the performance of the network, and the work can also be further extended to system dynamic stability conditions.

Declaration

The authors declare that there is no conflict of interest regarding the publication of this paper.

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References

[1] Zhang Y, Xu Y, Yang H, et al. Voltage regulation-oriented co-planning of distributed generation and battery storage in active distribution networks. Electr. Power Energy Syst. 2019;105:79–88.

[2] Hu Q, Bu S, Member S, et al. A Novel Voltage Regulation Strategy for Secure Operation of High Renewable Penetrated Distribution Networks with Different R / X and Topologies. 2019 IEEE Innov. Smart Grid Technol. - Asia (ISGT Asia). 2019;3229–3424.

[3] Abood HG, Sreeram V, Mishra Y. A New Algorithm for Improving the Numerical Stability of Power System State Estimation. IEEJ Trans. Electr. Electron. Eng. 2019;14:358–365.

[4] Mamo S, C R. Distribution system loss reduction in Addis Ababa north substation. IEEE Int. Conf. Innov. Power Adv. Comput. Technol. 2017;1–8.

[5] World Bank. Ethiopia renewable energy guarantees program report; 2019. < http://documents.worldbank.org/curated/en/363131558922556843/pdf/Ethiopia-Renewable-EnergyGuarantees-Program-Project.pdf> .

[6] Khan B, Singh P. The Current and Future States of Ethiopia's Energy Sector and Potential for Green Energy : A Comprehensive Study. Int. J. Eng. Res. Africa. 2017;33:115–139.

[7] Sambaiah KS. Loss minimization techniques for optimal operation and planning of distribution systems : A review of different methodologies. Int Trans Electr Energ Syst. 2019;1–48.

[8] Dixit M, Kundu P, Jariwala HR. Incorporation of distributed generation and shunt capacitor in radial distribution system for techno-economic benefits Number of Buses. Eng. Sci. Technol. an Int. J. 2017;20:482–493.

[9] Luo L, Gu W, Zhang X, et al. Optimal siting and sizing of distributed generation in distribution systems with PV solar farm utilized as STATCOM (PV-STATCOM). Appl. Energy. 2018;210:1092–1100.

[10] Essallah S, Khedher A, Bouallegue A. Integration of distributed generation in electrical grid : Optimal placement and sizing under different load conditions R. Comput. Electr. Eng. 2019;79:106461.

[11] Manikanta G, Mani A, Singh HP, et al. Simultaneous Placement and Sizing of DG and Capacitor to Minimize the Power Losses in Radial Distribution Network. Soft Comput. Theor. Appl. Adv. Intell. Syst. Comput. vol 742. Springer Singapore; 2019.

[12] Zhang L, Shen C, Chen Y, et al. Coordinated allocation of distributed generation , capacitor banks and soft open points in active distribution networks considering dispatching results. Appl. Energy. 2018;231:1122–1131.

[13] Jiangtao Ma, Jianshe Y, Kai Z, Shuhua G, et al. Master Plan Report of Wind and Solar Energy in Ethiopia. Addis Ababa, Ethiopia: HydroChina Beijing Engineering Corporation; 2012.

[14] Ministry Of Water and Energy. Ethiopia's Renewable Energy Potential; 2013. <https:// www.ctc-n.org/sites /www .ctcn .org /files /resources / africa _cec_session_3 _ministry_of_water_and_energy_ethiopia_beyene_220613 0.pdf > [Accessed on 19-10- 2020].

[15] RES4Africa Foundation . Integration of variable renewable energy in the national electric system of Ethiopia; 2019. < https:// www.res4africa.org/ wp-content/ uploads/2 019/07/ Abstract-Integration-Study Ethiopia.pdf > .

[16] World Bank. Ethiopia electrification program report; 2018. <http://documents.worldbank. org/ curated/en/686501520132423023/pdf/ETHIOPIA-PAD-02092018.pdf> [Retrieved on 29-01- 2020].

[17] Adefarati T, Bansal RC. Reliability assessment of distribution system with the integration of renewable distributed generation. Appl. Energy. 2017;185:158–171.

[18] Home-ortiz JM, Pourakbari-kasmaei M, Lehtonen M, et al. Optimal location-allocation of storage devices and renewable-based DG in distribution systems. Electr. Power Syst. Res. 2019;172:11–21.

[19] Prakash DB, Lakshminarayana C. Multiple DG placements in radial distribution system for multi objectives using Whale Optimization Algorithm. Alexandria Eng. J. 2018;57:2797–2806.

[20] Prasad PD, Reddy VCV, Manohar TG. Optimal renewable resources placement in distribution networks by combined power loss index and whale optimization algorithms. J. Electr. Syst. Inf. Technol. 2018;5:175–191.

[21] Roosta A, Khooban HEM. Optimization of radial unbalanced distribution networks in the presence of distribution generation units by network reconfiguration using harmony search algorithm. Neural Comput. Appl. 2019;31:7095–7109.
[22] Kumar S, Mandal KK, Chakraborty N. Optimal DG placement by multi-objective opposition based chaotic differential evolution for techno-economic analysis. Appl. Soft Comput. J. 2019;78:70–83.
[23] Kumar R, Mercy S, Kotapuri R. Optimal allocation of distributed generations using hybrid technique with fuzzy logic controller radial distribution system. SN Appl. Sci. 2020;2:1–14.
[24] Selim A, Kamel S, Jurado F. Efficient optimization technique for multiple DG allocation in distribution networks. Appl. Soft Comput. J. 2020;86:105938.
[25] Yarahmadi M, Shakarami MR. An analytical and probabilistic method to determine wind distributed generators penetration for distribution networks based on time-dependent loads. Electr. Power Energy Syst. 2018;103:404–413.
[26] Nawaz S, Sharma M, Tandon A. A New Approach for Power Loss Minimization in Radial Distribution Networks. Adv. Intell. Syst. Comput. vol 697. Springer Singapore; 2019. p. 1–7.
[27] Singh B, Jee B. Impact assessment of DG in distribution systems from minimization of total real power loss viewpoint by using optimal power flow algorithms. Energy Reports. 2018;4:407–417.
[28] Li Y, Feng B, Li G, et al. Optimal distributed generation planning in active distribution networks considering integration of energy storage. Appl. Energy. 2018;210:1073–1081.
[29] Mehta P, Bhatt P, Pandya V. Optimal selection of distributed generating units and its placement for voltage stability enhancement and energy loss minimization. Ain Shams Eng. J. 2018;9:187–201.
[30] Manas M, Jyoti B, Deben S, et al. Optimal Distributed Generator Sizing and Placement by Analytical Method and Fuzzy Expert System : a Case Study in Tezpur University , India. Technol Econ Smart Grids Sustain Energy. 2018;3:1–12.
[31] Ud F, Ahmad A, Ullah H, et al. Efficient sizing and placement of distributed generators in cyber-physical power systems. J. Syst. Archit. 2019;97:197–207.
[32] Ghazi MAT, Nazarian P, Safari A, et al. Multi-objective optimization model for optimal recon fi guration of distribution networks with demand response services. Sustain. Cities Soc. 2019;47:101514.
[33] Siahbalaee J, Rezanejad N, Gharehpetian GB, et al. Reconfiguration and DG Sizing and Placement Using Improved Shuffled Frog Leaping Algorithm. Electr. Power Components Syst. 2020;1–14.
[34] Das S, Das D, Patra A. Operation of distribution network with optimal placement and sizing of dispatchable DGs and shunt capacitors. Renew. Sustain. Energy Rev. 2019;113:109219.
[35] Saleh AA, Ibrahim AA. Multi-Objective Whale Optimization Algorithm for Optimal Allocation of Distributed Generation and Capacitor Bank. 2019 Int. Conf. Innov. Trends Comput. Eng. IEEE; 2019. p. 459–465.
[36] Gampa SR, Das D. Simultaneous optimal allocation and sizing of distributed generations and shunt capacitors in distribution networks using fuzzy GA methodology. J. Electr. Syst. Inf. Technol. 2019;6:1–18.
[37] Dixit M, Kundu P, Jariwala HR. Optimal integration of shunt capacitor banks in distribution networks for assessment of techno-economic asset. Comput. Electr. Eng. 2018;71:331–345.
[38] Ramos L, Araujo D, Rosana D, et al. Optimal unbalanced capacitor placement in distribution systems for voltage control and energy losses minimization. Electr. Power Syst. Res. 2018;154:110–121.
[39] Mekonnen T, Bhandari R, Ramayya AV. Techno-economic analysis of grid-integrated PV / wind systems for electricity reliability enhancement in Ethiopian industrial park. Sustain. Cities Soc. 2020;53:101915.
[40] IRENA. Future of solar Photovoltaic; 2019. < https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019.pdf>[Accessed on 28-8- 2021].
[41] Vartiainen E, Breyer C, Moser D, et al. Impact of weighted average cost of capital , capital expenditure , and other parameters on future utility - scale PV levelised cost of electricity. Photovoltaics. 2020;28:439–453.
[42] Haque M. Efficient load flow method for distribution systems with radial or mesh configuration. IET Gener. Transm. Distrib. 1996;143:33–38.
[43] Dixit M, Kundu P, Jariwala HR. Integration of distributed generation for assessment of distribution system reliability considering power loss , voltage stability and voltage deviation. Energy Syst. 2019;10:489–515.
[44] Hussain A, Arif SM, Aslam M, et al. Optimal Siting and Sizing of Tri-Generation Equipment for Developing an Autonomous Community Microgrid Considering Uncertainties. Sustain. Cities Soc. 2017;32:318–330.
[45] Murthy VVSN, Kumar A. Electrical Power and Energy Systems Comparison of optimal DG allocation methods in radial distribution systems based on sensitivity approaches. Int. J. Electr. Power Eenergy Syst. 2013;53:450–467.
[46] Teja BR, Kumar A. Optimal DG Placement in Unbalanced Mesh Distribution System for Loss Reduction and Voltage Profile Improvement. IEEE Int. Conf. Power Electron. Drives Energy Syst. 2014;1–5.

[47] Electrical Transient Analyser Program (ETAP). Ver 12.6.0. < https://etap.software.informer.com/12.6/ > [Retrieved on 27-01- 2020].

[48] Elsayed AM, Mishref M, Farrag S. Distribution system performance enhancement (Egyptian distribution system real case study). Int. Trans. Electr. Energy Syst. 2018;1–24.

[49] Ethiopian Electric utility.Current tariffs; 2018. < http://www.eeu.gov.et/index.php/current-tariff> [Accessed on 12-01- 2020].

[50] Imam AA, Al-turki YA, R SK. Techno-Economic Feasibility Assessment of Grid-Connected PV Systems for Residential Buildings in Saudi Arabia — A Case Study. sustainability. 2019;12:262.

[51] Eltawil N, Shamshiri M, Sulaiman M, et al. IMPROVEMENT OF BUS VOLTAGES AND LINE LOSSES IN POWER SYSTEM NETWORK THROUGH THE PLACEMENT OF CAPACITOR AND DG USING PSO. ARPN J. Eng. Appl. Sci. 2018;13:1–11.

[52] Shivarudraswam R, Gaonkar DN, Jayalakshmi NS. GA based Optimal Location and Size of the Distributed Generators in Distribution System for Different Load Conditions. IEEE Int. Conf. Power Electron. Intell. Control Energy Syst. 2016;1–5.