Power Loss Reduction and Voltage Profile Improvement of Radial Distribution System Through Simultaneous Network Reconfiguration and Distributed Generation Integration

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Abstract. In this paper Particle Swarm Optimization (PSO) based simultaneous distribution network reconfiguration and optimal Distributed Generation (DG) integration is conducted to significantly minimize the power losses and enhance the voltage profile of an electric power distribution network. The resource feasibility of solar and wind energy in Bahir Dar town was also assessed and the results revealed that solar energy production is more preferable. Backward/forward load flow analysis is deployed so as to determine the power losses and the voltage profile of each buses in the system. The proposed method is tested using MATLAB software in one of Bahir Dar distribution feeders called Bata feeder, and the objective function is evaluated by considering numerous constraints such as radiality, voltage profile, DG output limit and branch current limit. The simulation results obtained using simultaneous distribution network reconfiguration and DG insertion are encouraging. The voltage magnitude of all nodes is above the minimum threshold value and the minimum voltage is enhanced from 0.9150 pu to 0.9600 pu. In addition to this, the active and reactive power loss reduction are 54.42% and 46.37%, respectively. The cost effectiveness of the required DG size is also scrutinized and the payback period has become five years.

Keywords: Distributed generation · Network reconfiguration · Power loss · Voltage profile

1 Introduction

In an electric power distribution system, not only a substantial amount of power is lost but also the voltage profile of distant nodes from the main supplying substation are frequently below the minimum threshold value (0.95 pu) especially during heavy load conditions. This in turn exposes the end consumers to continuously suffer from under-voltage problem. G. Sasi Kumar, Dr. S. Sarat Kumar and Dr. S.V. Jayaram Kumar [9] in 2017 proposed the reconfiguration of an electrical distribution network for power loss

M. A. Delele et al. (Eds.): ICAST 2020, LNICST 384, pp. 244–258, 2021.
https://doi.org/10.1007/978-3-030-80621-7_18

reduction and voltage improvement. A new technique for reconfiguration of the network based on loss sensitivity factor to decide the switching combination and to achieve the best combination of switches for minimum active power loss and voltage profile enhancement which in turn improves the voltage stability in a radial distribution system is clearly presented. Only the active power loss is considered but the reactive power loss minimization has also been given equal emphasis especially when the feeder is connected to industries that large MVA inductive type of loads exist. I.J. Hasan, *M.R.Ab. Ghani and C.K. Gan* [1] in 2014 proposed optimum distributed generation allocation in a distribution system for power loss minimization and voltage profile enhancement using particle swarm optimization. The method had been tested on IEEE 33-bus radial distribution system and the results show that the stated method is effective in its performance. However, the feasibility study and the cost-effectiveness of distributed generation integration and reactive power loss reduction were not considered. Shreya Mahajan and Shelly Vadhera [2] in 2016 also presented optimal sizing and deploying of distributed generation unit by a modified multi-objective particle swarm optimization technique. The proposed method reduced the active power loss by 71.67% and maintained all node voltage magnitudes between the permissible limit but the real power loss can be significantly further minimized if the network topology is reconfigured optimally. R. Srinivassa Rao and others [7] in 2013 stated power loss minimization in distribution system using simultaneous network reconfiguration and distributed generation installation. Metaheuristic harmony search algorithm and sensitivity analysis are used for network reconfiguration and optimal DG location identification with an objective of real power loss minimization and voltage profile enhancement. The proposed method has been implemented on the IEEE 33-bus test system and the results obtained are encouraging. However, reactive power reduction has not been incorporated in the objective function besides any recent and effective optimization technique was not used.

From the literature reviewed, it is observed that all of the previous works focused on only active power loss minimization and voltage profile improvement in a radial distribution network. In this research, reactive power loss reduction, resource feasibility study of solar and wind type DG, possible location of tie-switches and cost-effectiveness of DG penetration on Bahir Dar power distribution network are also considered.

2 Resource Feasibility Study for Wind and Solar Energy

The solar and wind power plant energy outputs are strongly dependent on the sun radiation and the wind speed respectively which are stochastic in nature [10]. Therefore, the feasibility of resources for either solar and/or wind type DG installation at Bahir Dar town are first investigated before the study of their optimal size and appropriate bus location. The Ethiopian national metrology agency has recorded the sunshine hour of Bahir Dar city for ten consecutive years and these values are converted to solar irradiance. The results are depicted in Fig. 1 below.

Similarly, the wind speed at two meter above the ground for Bahir Dar town are collected from the metrology agency and these data are evaluated at forty meter as shown below (Fig. 2).

The solar irradiance of Bahir Dar city is from 4.0–5.5 kwh/m^2/day throughout the year whereas the cut-in wind speed is 2.71 m/s at 40 m height. Based on the resource

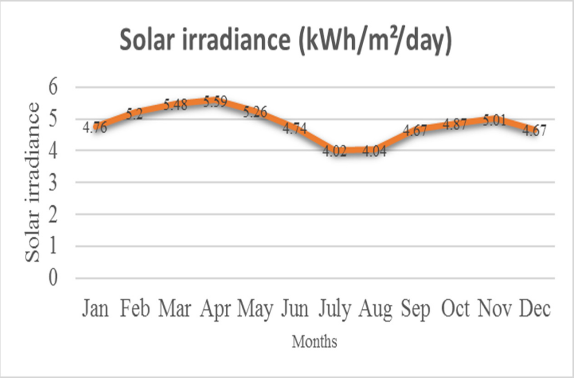

Fig. 1. Monthly average solar irradiance

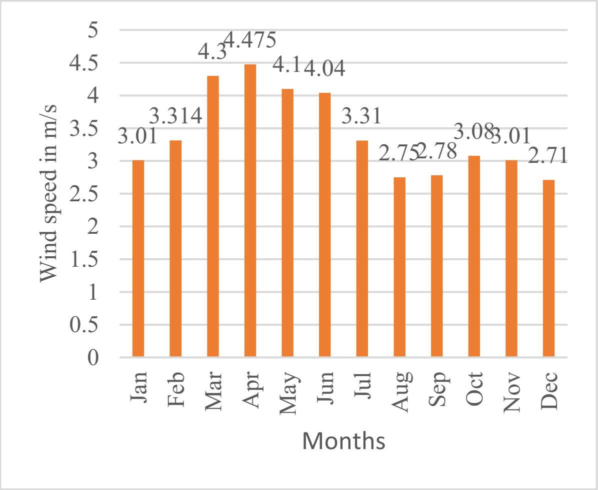

Fig. 2. Monthly wind speed at 40 m

data which are presented above, solar type DG is more preferable whereas the wind type DG is not feasible. Furthermore, solar type DG is more acceptable since it does not require any reactive power to inject electric power to the system to which it is connected whereas the wind type DG needs reactive power supply for its operation. On top of that, the wind speed continuously varies from hour to hour which in turn affects the stability of the power system and may not be able to cover the base load demand [15].

In general, considering the resource abundance of sunshine hour and wind speed in Bahir Dar city and considering the comparative benefits of PV versus wind, type I DG which injects only active power to the system is considered in this research for power loss minimization and voltage profile enhancement of a distribution network.

3 Optimal Tie-Switches Placement

Tie switches are normally open and are closed during reconfiguration to change topology of the network. Bahir Dar Distribution network consists of some sectionalize switches and two tie-switches. But only these two tie-switches are not sufficient enough to successfully reconfigure the network and it is a must to add at least two extra tie-switches. The best possible locations of these additional tie-switches are identified based on the following constraints.

i. Line length between non-consecutive nodes
   The tie-line shall connect two non-consecutive nodes whose separation distance is smaller so that the tie-line impedance will be minimum possible.
ii. Geographical constraints
   Even if the distance between two non-consecutive nodes is the smallest as compared to others, they can't be taken as a sending node and a receiving node for the tie-line provided that if it is geographically impossible for the over-head line installation. In other words, the overhead tie-line should be installed following the edge of the street road so that there will be ease of maintenance.
iii. Voltage profile
   The voltage profile of the sending end voltage has to be relatively better than the sending end voltage.

Considering the above-mentioned criteria for tie-switches placement, the new single line diagram of the network equipped with four tie-switches, in which the two tie-switches (36 and 37) are added in this research whereas tie-switches (34 and 35) already exist before, is presented below in Fig. 3.

Based on the tie-lines (34, 35, 36 and 37) location, the following four loops are constructed.

$$
\begin{aligned}
L_1 &= [3\ \ 4\ \ 5\ \ 10\ \ 14\ \ 15\ \ 16\ \ 17\ \ 34] \\
L_2 &= [11\ \ 12\ \ 13\ \ 23\ \ 24\ \ 25\ \ 26\ \ 35] \\
L_3 &= [8\ \ 18\ \ 19\ \ 20\ \ 21\ \ 29\ \ 30\ \ 36] \\
L_4 &= [22\ \ 27\ \ 28\ \ 31\ \ 37]
\end{aligned}
$$

Now, the main target of optimal network reconfiguration is that, which sectionalize line in each loop has to be opened so that an optimal and radial network structure with minimum possible power loss and better voltage profile can be obtained. The sectionalize lines to be opened are determined with PSO optimization as discussed in the coming sections.

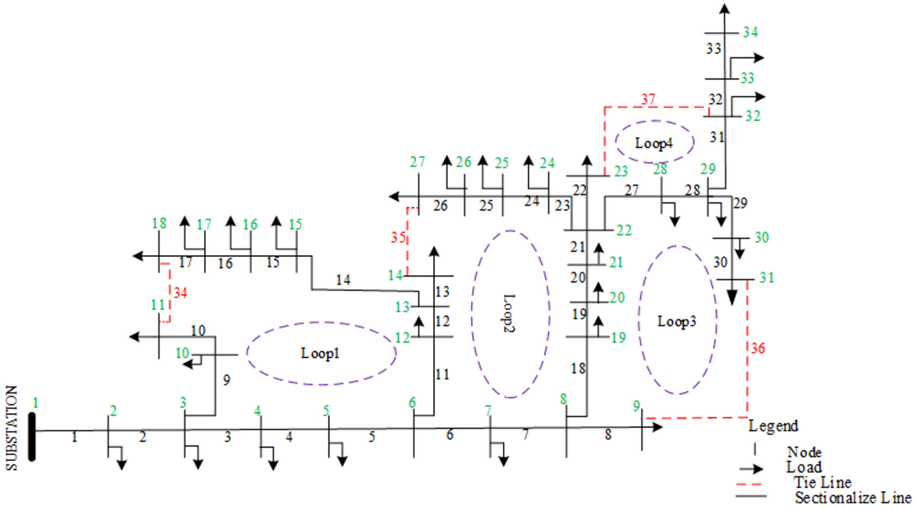

Fig. 3. Single line diagram of BATA feeder with tie-switches

4 Problem Formulation

4.1 Load Flow Analysis in Distribution System

The network shown in Fig. 4 is considered for optimization problem formulation of network reconfiguration. A set of recursive equations can be derived from this single line diagram so as to get the load flow equations of a radial distribution network.

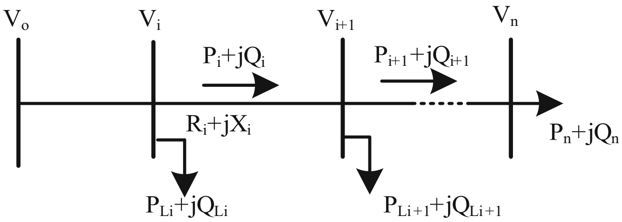

Fig. 4. Single line diagram of a radial distribution system

Active and reactive power losses between node i and $i + 1$ before network reconfiguration are formulated as follows [7].

$$\begin{aligned} P_{i+1} &= P_i - P_{Loss,i} - P_{Li+1} \\ &= P_i - \frac{R_i}{V_i^2}\left(P_i^2 + Q_i^2\right) - P_{Li+1} \end{aligned} \tag{1}$$

$$Q_{i+1} = Q_i - Q_{Loss,i} - Q_{Li+1}$$

$$= Q_i - \frac{X_i}{V_i^2}\left(P_i^2 + Q_i^2\right) - Q_{Li+1} \tag{2}$$

Now, the power losses equation in the line connecting bus i and bus i + 1 can be derived as:

$$P_{loss}(i, i+1) = \frac{R_i}{V_i^2}\left(P_i^2 + Q_i^2\right) \tag{3}$$

$$Q_{loss}(i, i+1) = \frac{X_i}{V_i^2}\left(P_i^2 + Q_i^2\right) \tag{4}$$

The total power losses of the feeder are therefore calculated by summing up the losses of the line sections as shown below.

$$f_1 = P_{T,loss} = \sum_{i=1}^{N} \frac{R_i}{V_i^2}\left(P_i^2 + Q_i^2\right) \tag{5}$$

$$f_2 = Q_{T,loss} = \sum_{i=1}^{N} \frac{X_i}{V_i^2}\left(P_i^2 + Q_i^2\right) \tag{6}$$

4.2 Distribution Network Reconfiguration

Let the apparent power flow from bus i to $i + 1$ after network reconfiguration be $P_i' + jQ_i'$.

The power losses between these buses after the network topology is altered can be formulated following similar procedures shown above.

$$P_{loss}'(i, i+1) = R_{i,i+1}\left(\frac{P_i'^2 + Q_i'^2}{V_i^2}\right) \tag{7}$$

$$Q_{loss}'(i, i+1) = X_{i,i+1}\left(\frac{P_i'^2 + Q_i'^2}{V_i^2}\right) \tag{8}$$

Total power losses of the system after network reconfiguration are:

$$f_3 = \sum_{i=1}^{N} P_{loss}'(i, i+1) \tag{9}$$

$$f_4 = \sum_{i=1}^{N} Q_{loss}'(i, i+1) \tag{10}$$

Now, the change in active power loss and reactive power loss before and after network reconfiguration which are the first objective functions in this scenario are determined as shown in Eqs. 13 and 14.

$$F_1 = \Delta P^R = \left(\sum_{i=1}^{N} P_{loss}(i, i+1) - \sum_{i=1}^{N} P_{loss}'(i, i+1)\right) \tag{11}$$

$$F_2 = \Delta Q^R = \left(\sum_{i=1}^{N} Q_{loss}(i, i+1) - \sum_{i=1}^{N} Q'_{loss}(i, i+1) \right) \tag{12}$$

Bus voltage is one of the most significant security and power quality indices. As a result, minimization of bus voltage deviation is chosen as the second objective. This objective function can be described as follows [5]:

$$F_3 = \sum_{i=1}^{N} (1 - V_i)^2 \tag{13}$$

Lastly, thus three individual objective functions [F_1, F_2 and F_3] are combined together to get one multi-objective (MOF) optimization problem as shown below. However, the power loss objective function is formulated as maximization problem whereas the voltage deviation objective function is minimization problem. Therefore, the third objective function is changed to maximization problem by multiplying negative.

There are numerous system constraints that must be considered and fulfilled in the process distribution network reconfiguration. These constraints are listed and explained below.

Voltage Constraint: According to the IEEE standard, voltage magnitudes should be maintained between 0.95 pu and 1.05 pu.

$$0.95 \leq V_i \leq 1.05$$

Current Constraint: Current at each branch must be less than or equal to its maximum capacity. This constraint can be described as:

$$I_{ij} \leq I_{ij}^{\max} \tag{14}$$

Radiality Constraint: The distribution network is supposed to remain radial after network reconfiguration is applied since protection schemes implementation will be relatively easier. In other words, the number of branches in a certain loop before reconfiguration must greater than the number of branches after the reconfiguration at least by one unit.

$$\sum_{i=1}^{M_i} (|S_i|) \leq M_i - 1 \tag{15}$$

Where M_i is the amount branches in the i$^{\text{th}}$ loop
S_i is the branch after reconfiguration

In general, the network reconfiguration problem formulation for power losses reduction and voltage profile improvement is as shown below.

$$\text{Maximize}$$

$$F = W_1 * \Delta P^R + W_2 * \Delta Q^R - W_3 * \sum_{i=1}^{N} \left((1 - V_i)^2 \right)$$

$$\text{Subjected to} \quad \begin{cases} 0.95 \le V_i \le 1.05 \\ I_{ij} \le I_{ij}^{\max} \\ \sum_{i=1}^{M_i} \left(|S_i| \right) \le M_i - 1 \\ W_1 + W_2 + W_3 = 1 \end{cases}$$

Where: W_1 and W_2 are the weighting factors given priority to reduction of real and reactive power losses, respectively.

W_3 is the weighting factor given priority to voltage profile improvement.

4.3 DG Sizing and Placement

DG insertion to a distribution system has numerous advantages viz. reduction of line losses, improvement of voltage profile, peak demand shaving, reduced environmental effects, and so on. However, it may lead to poor voltage profile and high-power loss if the DG size and location is not optimally determined. In this paper, PSO is used to allocate and select the optimal size of DG, and the objective function formulation along with system constraints and system modeling (depicted in Fig. 5) are shown below.

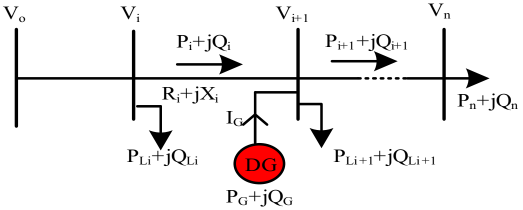

Fig. 5. Distribution network with DG

When DG is integrated to the distribution system as depicted in Fig. 6, the power loss equations derived above can be modified as:

$$P_{DG,Loss}(i, i+1) = \frac{R_i}{V_i^2}\left(P_i^2 + Q_i^2\right) + \frac{R_i}{V_i^2}\left(P_G^2 + Q_G^2 - 2P_iP_G - 2Q_iQ_G\right) \quad (16)$$

$$Q_{DG,Loss}(i, i+1) = \frac{X_i}{V_i^2}\left(P_i^2 + Q_i^2\right) + \frac{X_i}{V_i^2}\left(P_G^2 + Q_G^2 - 2P_iP_G - 2Q_iQ_G\right) \quad (17)$$

Net power losses reduction in the system is:

$$\Delta P_{loss}^{DG} = \frac{R_i}{V_i^2}\left(P_G^2 + Q_G^2 - 2P_iP_G - 2Q_iQ_G\right) \quad (18)$$

$$\Delta Q_{loss}^{DG} = \frac{X_i}{V_i^2}\left(P_G^2 + Q_G^2 - 2P_iP_G - 2Q_iQ_G\right) \quad (19)$$

As a result, the objective function can be formulated as shown below:

$$\text{Maximize}$$

$$F = W_1 * \Delta P_{loss}{}^{DG} + W_2 * \Delta Q_{loss}{}^{DG} - W_3 * \sum_{i=1}^{N} (1 - V_i)^2$$

$$\text{Subjected to} \quad \begin{cases} 0.95 \leq V_i \leq 1.05 \\ I_{ij} \leq I_{ij}{}^{\max} \\ P_G \leq P_G{}^{\max} \\ Q_G \leq Q_G{}^{\max} \\ W_1 + W_2 + W_3 = 1 \end{cases}$$

However, in this research type I DG is used since wind resource is not sufficient enough to generate the required power which is 1.25 MVA (50% of the total peak load). As a result, the reactive power constraint is not considered in this research because the power output from type I DG is only active power.

5 Simultaneous Network Reconfiguration and DG Allocation

In this scenario, the objective functions and constraints obtained before are merged together in order that the power loss reduction and bus voltage profile improvement will be significantly enhanced. Different weighting factors are also considered for active power loss reduction, reactive power minimization and voltage enhancement. More priority is given for active power loss reduction next to voltage profile upgrading.

$$\text{Maximize}$$

$$F = \sum_{i=1}^{N} W_1 * \left(\Delta P_{loss}{}^{R}(i, i+1) + \Delta P_{loss}{}^{DG}(i, i+1)\right) - \sum_{i=1}^{N} W_3 * (1 - V_i)^2$$

$$\text{Subjected to} \quad \begin{cases} 0.95 \leq V_i \leq 1.05 \\ I_{ij} \leq I_{ij}{}^{\max} \\ P_G \leq P_G{}^{\max} \\ \sum_{i=1}^{M_i} (|S_i|) \leq M_i - 1 \\ W_1 + W_2 + W_3 = 1 \end{cases}$$

6 Results and Discussion

Four separated scenarios are considered to test the effectiveness of the proposed method on power loss minimization and voltage profile enhancement. The total number of particles/populations for the simulation result are fifty while the minimum and maximum voltage magnitude are fixed to be 0.95 pu and 1.05 pu, respectively.

Scenario I: The existing system (base case) is simulated and the resulting voltage profile and power losses are depicted in Figs. 6 and 7, respectively.

Scenario II: The network topology is optimally reconfigured with the help the available sectionalize and tie-switches using PSO optimization without considering DG.
Scenario III: Type I DG is integrated with the network.
Scenario IV: The network is reconfigured simultaneous with DG installation.

The network reconfiguration simulation results reveal that the voltage profile of the system is significantly improved after the network is optimally altered as shown in Fig. 6 below (blue color). The minimum voltage before network reconfiguration was 0.9150 pu, and it is improved to 0.9467 pu after the topology is reconfigured using PSO optimization.

However, the voltage profile of some buses (6 7 8 9 and 11) is decreased after network reconfiguration is applied. This problem may happen most of the time since the topology of the network is changed. But the voltage profile of these buses is still above the minimum threshold value. Therefore, even if some buses voltage profile is affected when the network is altered, network reconfiguration results in remarkable voltage profile improvement.

Optimal distribution network reconfiguration not only enhances the voltage profile of the system but also it reduces the power losses substantially as shown in Fig. 7 below. The active power loss is reduced to 196.48 kW from 307.12 kW (base-case) whereas the reactive power loss is reduced to 194.16 kVAr from 258.70 kVAr (base-case). In other words, the active and reactive power loss reduction due to optimal network reconfiguration alone are 36.13% and 24.45%, respectively.

As shown in Fig. 6 (green color), the voltage profile of all buses except the first bus are moderately improved after 0.01pu DG size is connected at the end bus. The minimum voltage before the installation of DG was 0.9150pu but it is enhanced to 0.9369pu due to the integration of this DG.

Similarly, the power losses reduction when DG is connected to bus 34 is presented in Fig. 7 (scenario III). The active and reactive power losses are considerably minimized. In other words, the active power loss reduction is 34.06% whereas the reactive power loss reduction is 32.13%.

The power losses minimization and voltage profile enhancement of a distribution network using network reconfiguration and DG installation separately, are clearly discussed before. Both these methods can't achieve appreciable results in loss reduction and voltage improvement when they are considered individually. The network reconfiguration technique in parallel with DG installation was conducted using PSO algorithm in order that the voltage profile and loss minimization can be significantly enhanced.

As it can be observed all bus voltages after the network is reconfigured in parallel with DG installation are maintained above the minimum nominal value. For instance, the minimum voltage profile of the network before applying any techniques (base case) was 0.9150 pu and it is substantially upgraded to (0.9600 pu) when the proposed method is applied.

Likewise, Fig. 7 presents the network percentage total active and reactive power loss reduction when the afro-mentioned distribution network performance enhancement methods are considered. The results from this scenario, as it can be noted in Figs. 6 and 7 below, are very encouraging as compared with the results from when these methods are used exclusively. The active and reactive power loss reduction are 54.42% and 46.37%,

Table 1. Result summary of the proposed method

Scenarios	Performance measurements	
Scenario I	Switches Opened	33, 34, 35 & 36
	Active power loss (kW)	307.12
	Reactive power loss (kVAr)	258.70
	Minimum voltage (pu)	0.9150
	Maximum voltage deviation	8.5000%
	Average computing time (ms)	65
Scenario II	Switches opened	14, 23, 31 & 36
	Active power loss (kW)	196.48
	Reactive power loss (kVAr)	194.16
	Active power loss reduction	36.02%
	Reactive power loss reduction	24.95%
	Minimum voltage (pu)	0.9467
	Maximum voltage deviation	5.3300%
	Average computing time (ms)	130
Scenario III	Switches opened	33, 34, 35 & 36
	Size of the DG (MW)	1
	Bus location of the DG	34
	Active power loss (kW)	202.51
	Reactive power loss (kVAr)	175.59
	Active power loss reduction	34.06%
	Reactive power loss reduction	32.13%
	Minimum voltage (pu)	0.9369
	Maximum voltage deviation	6.3100%
	Average computing time (ms)	95
Scenario IV	Switches opened	14, 23, 31 & 36
	Size of the DG (MW)	1
	Bus location of the DG	31
	Active power loss (kW)	139.89
	Reactive power loss (kVAr)	138.74
	Active power loss reduction	54.42%
	Reactive power loss reduction	46.37%
	Minimum voltage (pu)	0.960
	Maximum voltage deviation	4.000%
	Average computing time (ms)	215

respectively. The convergence for network reconfiguration suppresses DG integration this due to the time required for each particle to try all available sectionalize and tie-switches combination for better performance.

In general, the results from all the scenarios are summarized and presented in Table 1. The results show that each method plays an important role, when they are applied independently, in the total active and reactive power losses minimization and system voltage profile improvement.

However, it can be noted that the last scenario which is simultaneous network reconfiguration and DG allocation has a paramount importance for loss minimization and voltage profile enhancement.

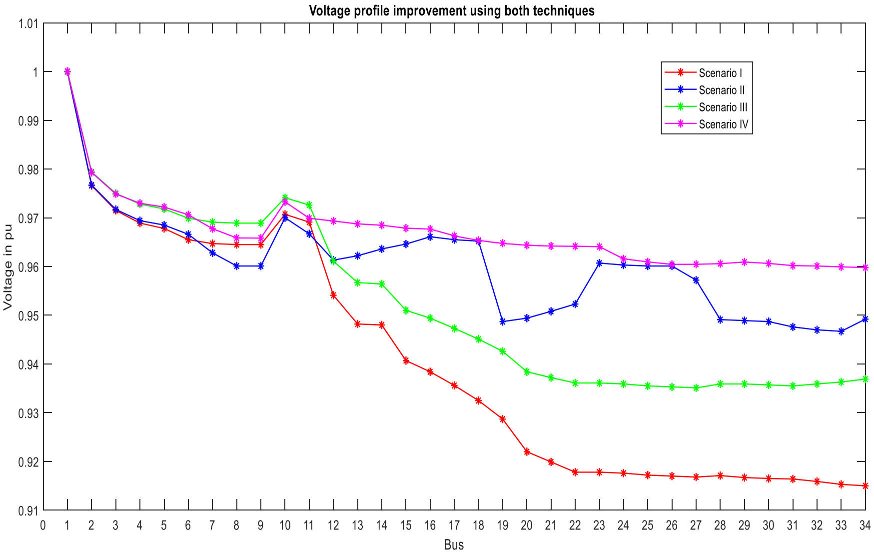

Fig. 6. Results comparison

7 Cost Analysis and Payback Period

The cost effectiveness of DG integration on the existing network is determined from the saving cost which is the difference of the losses in dollar before and after applying the proposed techniques. The existing network total power loss was 307.12 kW. In other words, 0.1098 million $/year is lost. After the proposed method is used, the power loss is reduced to 139.98 Kw that means 0.0500 million $/year is lost. This indicates that 0.0598 million $/year can be saved when 1 MW solar power plant is installed in conjunction with re-structuring the network topology.

The payback period is the ration of the capital cost to the saving cost as shown in Eq. (20) below.

$$Payback\ period = \frac{Capital\ cost(dollar)}{Saving\ cost\left(dollar/year\right)} \tag{20}$$

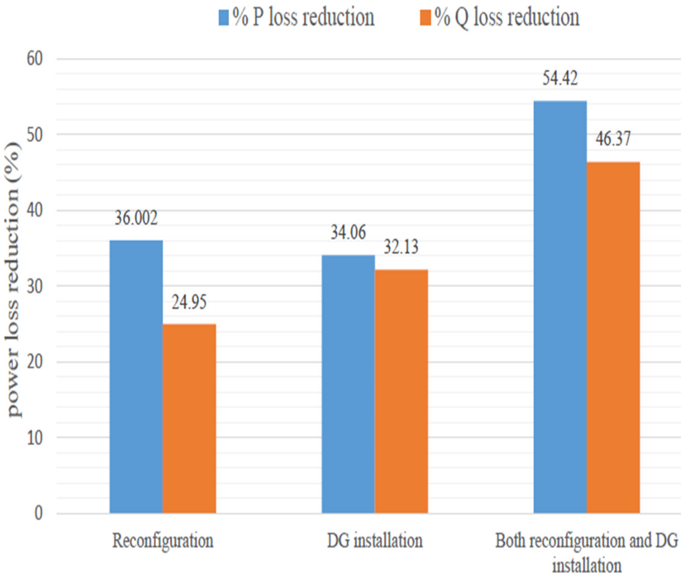

Fig. 7. Power loss reduction

The saving cost is already determined before whereas the capital cost is calculated by summing the cost for solar panel, inverters, battery, installation cost and maintenance cost. The initial capital cost for solar panel, inverters and batteries is 0.2093 million$, 0.0857 million$ and 0.00738 million$, respectively. The installation cost and maintenance cost are assumed to be no more than 0.00341 and 0.0003451 million $/year, respectively. Summing all these costs yields to total capital cost of 0.306 million$.

When the capital cost and the saving cost are substituted in Eq. (20) above, the payback period becomes around five years. This means that 0.05941 million $/year can be saved after five years from when the solar power plant is installed to the system.

8 Conclusion

In this research work, an effective method has been anticipated to reconfigure distribution networks simultaneous with optimal DG units' installation. In addition, various loss reduction methods (only network reconfiguration, only DG installation, DG installation simultaneous with network reconfiguration) are also simulated to confirm the superiority of the proposed method. One of the proficient meta-heuristic optimization techniques called PSO is used to simultaneously reconfigure and allocate DG units. The proposed method is tried on Bahir Dar distribution network specifically on BATA feeder at heavy load condition.

The simulation results show that 167.14 kW active power can be saved by applying the proposed method and also the entire buses voltage profile are maintained within the IEEE acceptable range. In other words, the active and reactive percentage power losses reduction due to this method are 54.42% and 46.37%, respectively and the minimum voltage profile is 0.9600 pu which confirms that simultaneous network reconfiguration and DG installation method is most effective in reducing power losses and improving the voltage profile compared to other methods.

The cost effectiveness and payback period are also assessed in detail. The results showed that 0.05941 million dollars can be saved in each year after five years from when the DG unit is integrated to the system.

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