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Improving the Voltage Stability of Distribution Network Using Capacitor Banks and PV Arrays Based on OpenDSS

Mohammed Qasim Majeed [1], Ali Jafer Mahdi [2], Manal Hussein Nawir [1],

[1] Department of Electrical and Electronics Engineering, University of Kerbala, Karbala 56001, Iraq
[2] College of Information Technology Engineering, Al-Zahraa University for Women,56001 Karbala, Iraq.

Abstract. This study endeavors to enhance the voltage profile, mitigate energy losses, and narrow the gap between electricity generation and consumption in the Al-Gharab distribution network in Al-Qadisiyah, Iraq. The Al-Gharab radial distribution network is afflicted by voltage drops and fluctuations, frequent power interruptions, and power losses. The researchers are studying the potential of supporting the network with the Capacitor Banks (CBs) and incorporating Photovoltaic arrays (PV arrays) as a means of improving its performance. The proposed system is simulated using Matlab and Open Distribution System Simulator (OpenDSS). The optimal placement and size of the CBs are determined using the AutoAdd Optimization (AAO) technique, while the optimal size and location of PV arrays are determined by implementing the Archimedes Optimization Algorithm (AOA). The proposed system is simulated and the results are analyzed and extracted under various scenarios as follows: a. Base case system analysis, b. Integration of PV arrays, c. Integration of CBs without PV arrays, and d. Integration of CBs with PV arrays. Also, the CBs integration contains multi scenarios. The results showed that the best improvement of the network performance was obtained in the case of integration of the CBs with PV arrays, especially the scenario of integration of three units of CBs with PV arrays. Where the minimum voltage improved from (0.91848 pu) to (0.975 pu), and the total active and reactive power losses were decreased by (85 %) and (51 %) respectively.

Keywords: AutoAdd Optimization algorithm, Open Distribution system simulator, Capacitor banks, Photovoltaic arrays, Voltage profile.

1. Introduction

The detrimental impacts brought about by conventional carbon-based fuels have played a significant role in driving the growing trend of embracing renewable energy sources. Among the various options available, solar photovoltaic arrays (PV arrays) stand out due to their numerous advantages. Integrating PV arrays into distribution networks has economic, technical, and environmental benefits. Firstly, PV arrays can be cost-effective, have low maintenance requirements, and they widely available [1]. Secondly, PV arrays integration can lead to a reduction in power losses, minimizing feeder loading, and improving voltage profile, thereby improving the overall efficiency of the system. PV arrays can enhance the load ability and voltage stability of the distribution system when properly placed and sized [2]. Thirdly, PV arrays are considered environmentally friendly, where widespread use of PV arrays could lead to a reduction in CO2 emissions and delay the depletion of fossil fuels [3].

On the other hand, the installation of the CBs within the distribution network can generate reactive power, which can enhance the voltage at load buses and decrease the power losses within the distribution network. Consequently, this results in a reduction of the reactive power demand from the source [4]. As a result, the combined integration of PV arrays and CBs is expected to decrease power losses in the distribution system, improve the voltage profile, and ultimately enhance the overall performance of the distribution system. However, in order to realize these aforementioned benefits and address voltage deviation issues, it is imperative to conduct an investigation into the optimal placement and sizing of PV arrays and CBs through the utilization of appropriate optimization tools [5].

In recent times, numerous researchers have employed various metaheuristic optimization techniques to distribute the distributed generators placement across distribution systems. The utilization of the genetic algorithm (GA) technique was explored in the study [6] to identify the optimal allocation and size of DG, it was subsequently implemented on a 14-bus distribution system. The authors in [7] utilized Mixed Integer *Linear* Programming (*MILP*) optimization algorithm to identify the impact of renewable energy generation sources and energy storage systems on an electricity grid. The authors in [8], [9] utilized the particle *swarm* optimization (PSO) algorithm or its improved iterations to effectively mitigate the power losses experienced within distribution networks. In a similar vein, the algorithm of grey *wolf* optimization (GWO) was adopted in [10], [11] to effectively minimize both active and reactive power losses, while simultaneously improving the voltage profile of diverse distribution systems. The optimal operation of CBs is of utmost importance for distribution systems at any step of automation [12]. The placement of CBs at non-optimal locations may lead to a rise in the overall power losses of the system and an increase in the costs. Consequently, this would have a contrary impact on the desired outcome. Due to this reason and others, various optimization techniques are employed to ascertain the most suitable positioning of capacitors for a particular distribution system [13]. Diverse techniques in optimization, such as Particle *Swarm* Optimization (PSO) and the Whale *Optimization* Algorithm (WOA), can be employed to ascertain the most advantageous location and magnitude of CBs [14][15]. The objective of this study is to integrate PV arrays and CBs individually and then combine them together to determine their impacts on the Al-Gharab distribution network. Also, to determine the optimal number, size, and location of the PV arrays and CBs to suit the proposed network conditions.

2. Optimization Algorithms

One of the two algorithms employed in this study is the AOA algorithm. By establishing COM interfacing between MATLAB and OpenDSS programs, the steps of the algorithm presented in [16] were implemented to optimize the placement and size of PV arrays for the proposed network. While the AAO technique was employed to identify the optimal placement and size of the CBs.
The "AutoAdd" functionality is a mode within the OpenDSS software that facilitates the analysis of the most advantageous placements for generators and CBs. These algorithms are employed to minimize power loss and improve the voltage profile in distribution systems. The AAO technique in OpenDSS derives advantages from its direct access to the compensation current matrix during the solution as a result of the iterative approach utilized to search for unknown voltages and currents. Moreover, the speed of convergence of this algorithm's solution increases due to the constancy of the system's admittance matrix. The Improvement Factor percentage indicates the location of the next-best power supply [17]. Figure 1 shows the flow chart of the AAO technique.

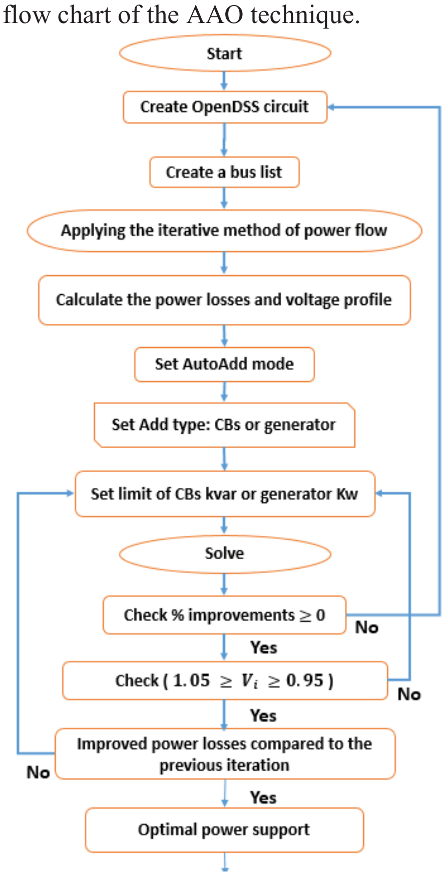


Fig. 1. Flow chart of AAO technique

A. Objective Function and System Constraints

1)The Objective Function: This work aims to optimize the voltage stability by minimizing the active and reactive power losses in the system network and reducing the voltage deviation. To achieve this goal, the objective function which quantifies the desired outcomes, is formulated as in Equation (1):

$$F(k) = min\,\{f_1(k) \;+\; f_2(k)\} \qquad (1)$$

Where: $f_1(k)$: represents the objective function of the power losses as shown in Equation (2)

$$f_1(k) = \sum_{i=1}^{br} R_i \times I_i^2 \qquad (2)$$

Where: $br, R_i\,, I_i$ represent branches number, i^{th}branch resistance, and i^{th} branch current respectively.
$f_2(k)$: represents the objective function of the average voltage deviation index as shown in Equation (3)

$$f_2(k) = \sum_{k=1}^{b} |1 - V_k|^2 \qquad (3)$$

Where: b and V_k represent bus number, and voltage at k^{th} bus respectively.

2) The system constraints: Generally, the limitations imposed on the distribution network consist of both the constraint pertaining to the topological structure as well as the operational constraint.
1. The constraint pertaining to the topological structure: The operational configuration of the distribution network should conform to a radial network, thereby prohibiting the existence of loops and islands within the network.
2. Operational constraint: One of the primary operational constraints in distribution networks pertains to the voltage levels, specifically the lower and upper thresholds. It is imperative for the network voltages to remain within the acceptable range of (0.95 to 1.05) to uphold the stability of the network [18].

$$V_{i\,min} \le V_i \le V_{i\,max} \qquad (4)$$

Where: $V_{i\,min}$, refers to the minimum i_{th} bus voltage limit witch equal to 0.95, while $V_{i\,max}$ refers to maximum i_{th} bus voltage limit witch equal to 1.05.
The second limitation pertains to the boundaries of active and reactive power injection, as the power stemming from the integration of the PV arrays and CBs should not surpass the thresholds of the utmost power demand and the power losses as shown in Equations (5) and (6).

$$\sum_{i=1}^{n} P_{pv\,i} \;\le\; P_D \;+\; P_{LT} \qquad (5)$$

Where: n, refers to the number of PV arrays, while P_D refers to the total active power demand.

$$Q_c \;\le\; Q_D \;+\; Q_{LT} \qquad (6)$$

Where: Q_c , refers to the total compensated reactive power from PV arrays and CBs, while Q_D refers to the total reactive power demand.

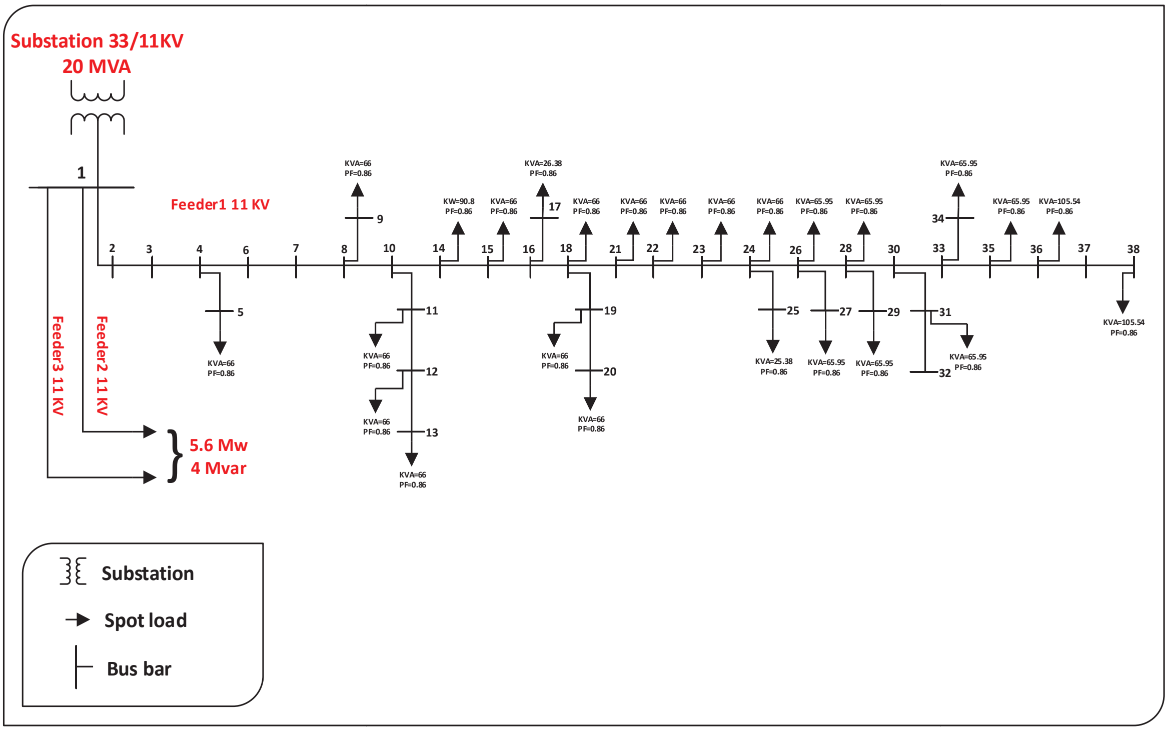


Fig. 2. Single line diagram of the Al-Gharab network.

3. Results and Analysis

A. The Proposed Network

The proposed electrical network pertains to the Al-Gharab region, situated approximately 80 km distant from Al-Diwaniyah, Iraq. Figure 2 illustrates the proposed network's single-line diagram. The aggregate active power entering the network is 7.19 MW, while the overall reactive power is equivalent to 5.18 Mvar. The foundational capability of the system is 10 MVA, and the foundational voltage is 11 kV.

B. Cases Studied

In this study, various scenarios were analyzed, and each scenario was individually examined for the purpose of contrasting and identifying the most optimal scenario with regard to network performance. The simulations were executed as follows: 1. Base case system analysis, 2. Integration of PV arrays, 3. Integration of CBs without PV arrays, and 4. Integration of CBs with PV arrays.

1) (Case 1) Base case system analysis:

At the outset, the load flow analysis was conducted on the proposed network to determine the voltage profile and power loss. Where, the total active power losses were equal to (52.26 KW), while the total reactive power losses were equal to (350 KVAR). The maximum bus load values were employed to calculate the voltage profile of the network. According to the findings derived from the voltage profile that shown in Fig.3 it can be observed that the voltages of a majority of the network's buses were lower than the acceptable threshold.

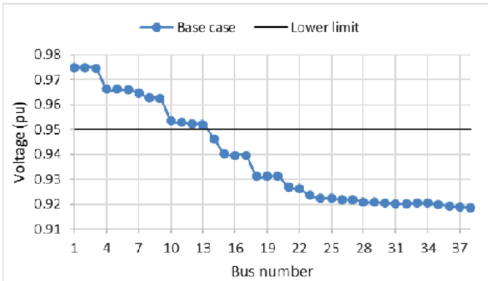


Fig. 3. Voltage profile of the base case

2) (Case 2): Integration of PV arrays:

The simulation involved the incorporation of the PV arrays into the grid, where the AOA Algorithm was utilized to optimize the optimal placement and size. The optimization calculations were based on the upper limits of loads, temperature equal to (48°), and solar irradiation equal to (900 w/m^2). Temperature and solar irradiation data for July shown in Fig.4 were adopted according to [19]. Also, the daily load shape data shown in Fig.5 were estimated according to the estimation of [20]. The load shape was adopted for the daily monitoring (through 24 hours) of the voltage limits in the bus that has the lowest voltage in the grid.

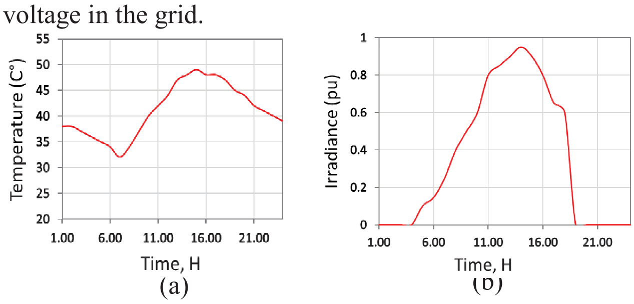


Fig. 4. (a) daily temperature curve; (b) daily irradiance shape

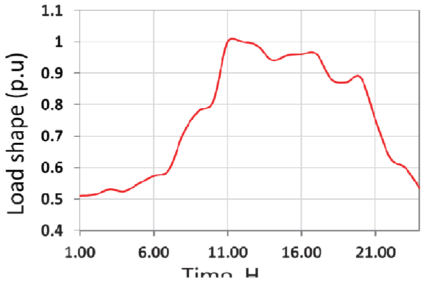


Fig. 5. Daily load shape

The optimization outcomes of the AOA algorithm are illustrated in Table I.

Table I. The optimization results of case 2

Three PV arrays	Optimal size (KW)	Optimal location	Power factor
1	760	Bus 24	0.9
2	280	Bus 28	0.9
3	245	Bus 18	0.9

According to the voltage profile shown in Fig.6, the minimum voltage improved by (5%) compared with the base case, where the minimum voltage in the base case is equal to 0.91848 at bus 38, while in case B, it is equal to 0.96363 at bus 38. Also, the total active power losses decreased by (80 %), additionally, the total reactive power losses decreased by (40 %). The power losses of case 2 are shown in Fig.7.

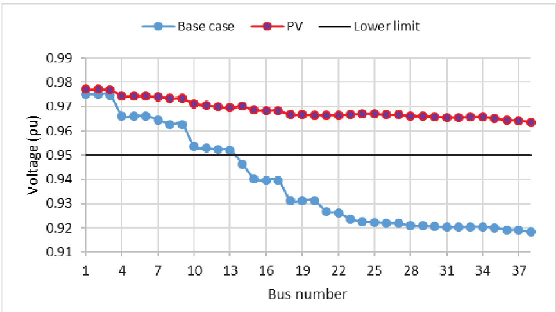
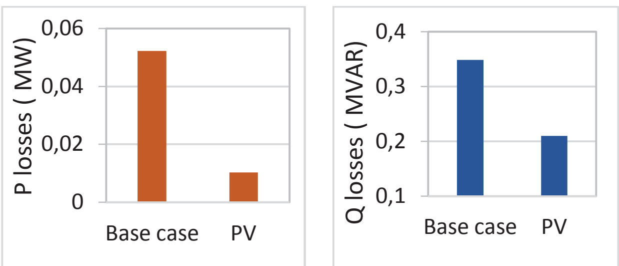


Fig. 6. Voltage profile of the case 2 (integration of PV arrays)



(a) (b)

Fig. 7. The power losses of case 2, (a) total active power losses; (b) total reactive power losses

3) (Case 3): Integration of CBs Without PV arrays:

The placement of CBs was optimized using the AAO technique. The optimization calculations were conducted based on the upper limits of the loads. To compare and identify the optimal scenario, the simulation procedure for CBs integration was performed in three different scenarios, which are as follows: Integration of one unit of CBs, Integration of two units of CBs, and Integration of three units of CBs. The outcomes of the optimization calculations are described in Table II.

TABLE II. The optimization results of case 3

Integration scenario	CBs size (KVAR)	CBs location	Min voltage	Total power losses (P - Q)
Base case	-------	-------	0.91848 @ bus 38	0.0522 MW - 0.348916 MVAR
One unit of CBs	950	bus 26	0.95097 @ bus 38	0.0433 MW - 0.321534 MVAR
Two units of CBs	510, 530	bus 28, bus 18	0.95057 @ bus 38	0.0414 MW - 0.304931 MVAR
Three units of CBs	400, 380, 420	bus 30, bus 18, bus 14	0.95002 @ bus 38	0.0400 MW - 0.291318 MVAR

The voltage profile presented in Fig.8 demonstrates the beneficial impact of incorporating the CBs on the network's performance in relation to the voltage profile. Specifically, the addition of the CBs led to an enhancement in the minimum voltage within the network from 0.918 to 0.95, as compared to the base case. Furthermore, the analysis reveals that there are no discernible disparities among the three scenarios, with the exception of the third scenario exhibiting a slight preference for buses (10 to 20).

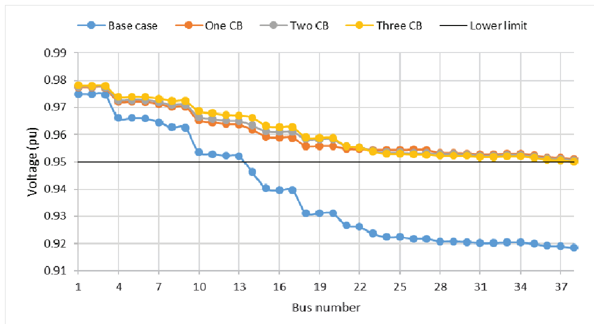
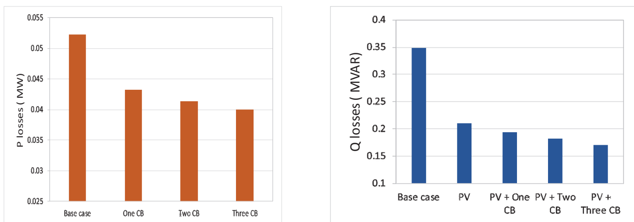


Fig. 8. Voltage profile of the case 3 (integration of CBs without PV arrays)

Regarding the power losses shown in Table II, the integration of the CBs into the network contributed to reducing both the total active power losses by (23 %) and the total reactive power losses by (16 %). The values of the total power losses are graphed in Fig.9, with their corresponding CBs number.



(a) (b)

Fig. 9. The power losses of case 3, (a) total active power losses; (b) total reactive power losses

The voltage of bus 38 was the lowest in the grid. Therefore, the voltages of bus 38 were monitored over 24 hours to determine the behavior of the network through this bus, taking into account the daily load shape. The voltage monitoring results are shown in Fig.10. We note that adding the CBs contributes effectively in improving the voltage profile. Due to the lack of distributed power sources, the voltage profile declines when the demand for power increases until it reaches the lowest point, specifically at 1:00 PM, so the integration of both PV arrays and CBs was simulated in the next scenario to know the network behavior.

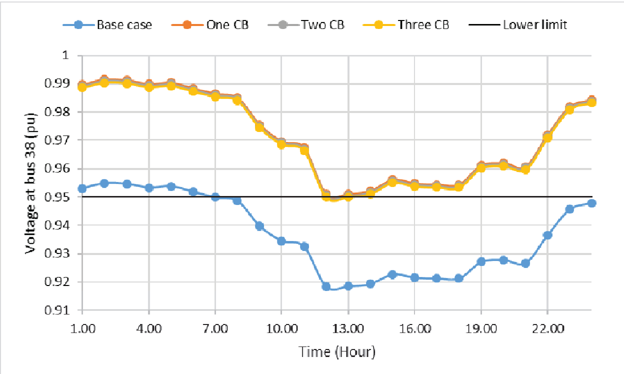


Fig. 10. The voltage profile of bus 38 in case 3

4) (Case 4): Integration of CBs with PV arrays:

This case is similar to the previous case but with the presence of the PV arrays. Where CBs placement was optimized using the AAO technique and in case of the maximum loads. Also, three scenarios were discussed to identify the optimal scenario as follows: Integration of one unit of CBs, Integration of two units of CBs, and Integration of three units of CBs. The outcomes of the optimization calculations are described in Table III.

TABLE III. The optimization results of case 4

Integration scenario	CBs size (KVAR)	CBs location	Min voltage	Total power losses(P - Q)
Base case	-------	-------	0.91848 @ bus 38	0.0522 MW - 0.348916 MVAR
PV arrays	-------	-------	0.96363 @ bus 38	0.0102 MW - 0.209706 MVAR
PV+ one unit of CBs	430	bus 16	0.97341 @ bus 38	0.0090 MW - 0.194333 MVAR
PV+ two units of CBs	200, 195	bus 36, bus 11	0.97484 @ bus 38	0.0088 MW - 0.181751 MVAR
PV + three units of CBs	140, 130, 120	bus 38, bus 12, bus 19	0.97568 @ bus 38	0.0085 MW - 0.170662 MVAR

Also, the voltage profile of the network in this case is shown in Fig.11, While the total active and reactive power losses are shown in Fig.12. and Fig. 13 respectively.

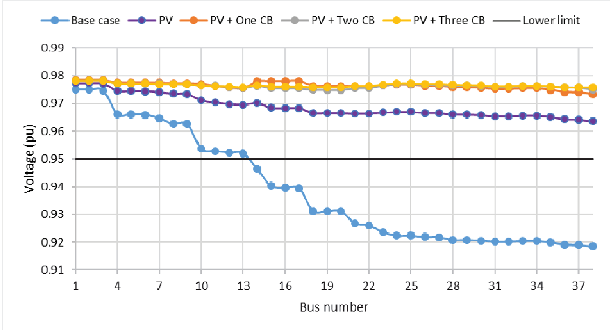


Fig. 11. Voltage profile of the case 4 (integration of CBs with PV arrays)

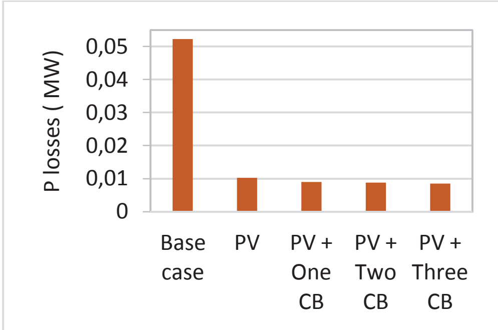


Fig. 12. The total active power losses of case 4

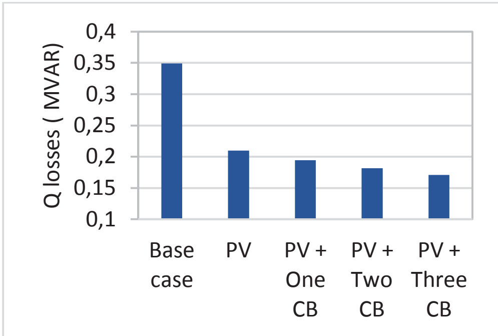


Fig. 13. The total reactive power losses of case 4

According to the voltage profile and power loss results shown in Fig. 11, Fig. 12, and Fig. 13 respectively, the integration of both PV arrays and CBs (Case 4) is considered the best compared to the other cases. Where the minimum voltage increased from (0.91848 pu) to (0.975 pu) compared with the base case. On the other hand, the total active and reactive power losses decreased by (85 %), and (51 %) compared with the base case.

In regards to the comparison amongst the three scenarios pertaining to this particular case, it is worth noting that there exist no discernible disparities between said scenarios. From a technical perspective, there exists a minuscule inclination towards the third scenario (PV + three units of CBs), however, from an economic standpoint, it is more advantageous to adopt the first scenario (PV + one unit of CBs) given its appropriateness in exploiting smaller spaces for the integration of the CBs units, as well as the costs associated with the construction and maintenance of the CBs units are lower in comparison with the third scenario.

Also, with regard to the daily monitoring of the voltage profile of the bus with the lowest voltage in the network, bus 38 is still the weakest bus in the network and its voltage profile is shown in Fig.14. The performance of the network is evaluated through this bus and we notice the superiority of the voltage profile in this case compared to the other cases, as it was observed that there is a gradual increase in the voltage as the load on the bus increases.

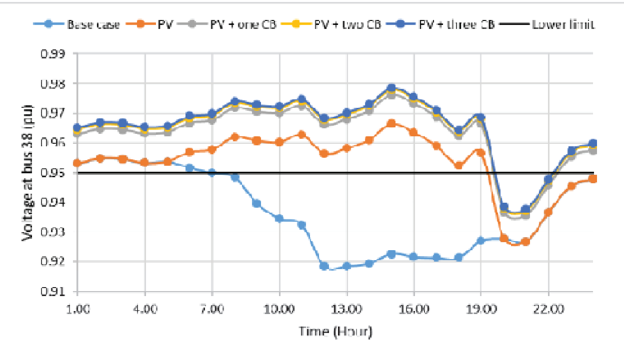


Fig. 14. The voltage profile of bus 38 in case 4

4. Conclusions

In this study, the integration of capacitor banks and PV arrays was simulated to improve the performance of the Al-Gharab distribution network in Al-Qadisiyah, Iraq by reducing the total active and reactive power losses and reducing the voltage deviation to improve the voltage stability. The simulation results showed the beneficial impact of incorporating the CBs and PV arrays on the network's performance, the best case is case 4 (Integration of CBs with PV arrays), where minimum voltage improved from (0.91848 pu) to (0.975 pu) compared with the base case. Also, the total active and reactive power losses were decreased by (85 %) and (51 %) respectively. Additionally, the results showed that there are no discernible disparities between the three scenarios in the integration of CBs units. But, from a technical perspective, there exists a minuscule inclination towards the third scenario (PV + three units of CBs), however, from an economic standpoint, it is more advantageous to adopt the first scenario (PV + one unit of CBs) given its appropriateness in exploiting smaller spaces for the integration of the CBs units, as well as the costs associated with the construction and maintenance of the CBs units are lower in comparison with the third scenario.

This study proved the potential positive impact of integrating PV arrays and CBs in the Al-Gharab distribution network. So, it opens horizons for future work to research and study other types of available power resources in the Al-Gharab region for economic and technical comparison with the PV arrays.

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