

Comparative Analysis of AC and DC Distribution Networks for Optimal Integration of Multiple Photovoltaic Distributed Generation

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Article Info	ABSTRACT
Article history: Received , 15/03/2024 Revised , 20/08/2024 Accepted , 15/10/2024	In recent years, Direct Current Networks (DCNs) have attracted researchers and scientists in high-voltage transmission lines, Medium-Voltage Distribution Networks (MV-DN), and microgrids. This is due to the many benefits they offer compared to traditional Alternating Current Networks (ACNs). These advantages can only be seen under specific criteria and conditions concerning the energy source, the network, and the load. The studies on this topic came up with outstanding results regarding implementing DCN in different applications like photovoltaic generation and battery storage systems. This paper focuses on the integration of Photovoltaic Distributed Generation (PVDG) into MV-DN using the standard IEEE 33-bus ACN and DCN. To make a comparison of the outcomes, an objective function consists of minimizing the Active Power Losses (APLs) and improving the Voltage Profile (VP) using a metaheuristic algorithm called Particle Swarm Optimization (PSO). This algorithm properly allocates and sizes the PVDG unit into the Radial Distribution Network (RDN). The findings show a decrease in APLs and an improvement in the VP after the installation of the PVDG in both networks, with much better results for DCN compared with those of ACN.
Keywords: Optimal integration Distributed generation Photovoltaic station Metaheuristic algorithm Radial network Direct current Voltage profile	

I. Introduction

The rapid growth of the world population has resulted in an exponential increase in energy demand. Thus, governments around the world are betting on Renewable Energy Resources (RERs) and moving away from fossil fuels to meet the growing demand on the one hand and reduce greenhouse emissions on the other [1]. RERs have very little effect on the environment or human health, but the power they deliver is intermittent and unstable, which makes it hard to predict and monitor [2]. However, new technologies have made RERs reliable, less expensive, and more efficient [3].

One of these technologies is Distributed Generation (DG) which is a term used to describe the production of electricity in a decentralized way, meaning that it is produced locally and near the customer [4]. This form of energy production is generally based on RERs like solar; however, the integration of a PV station into the grid poses many challenges because of the significant fluctuations in its output power brought on by climate conditions such as the erratic nature of solar radiation and environmental temperature [5]. PVDGs are among the best solutions to address the integration problem by using different techniques to place the DG in the optimum position with the optimum production size [6].

Researchers have adopted a new method that consists of using DCN over ACN. This approach offers many advantages regarding power loss minimization, VP improvement, and other technical, economic, and environmental properties. Knowing that PV panels deliver direct current makes their connection to a DCN more convenient, so fewer power converters are needed, resulting in a decrease in investment costs [7].

DC links were first used in high-voltage networks to transmit large amounts of electricity over great distances, decreasing power losses and facilitating the monitoring of power flow, therefore connecting offshore wind farms to the main grid [8]. and because neither the frequency nor the reactive power is included in the mathematical analysis, DCN is more resilient and easier to control than ACN.; however, development is still ongoing regarding the planning and management of distribution DCNs [9].

Various methods have been put up by authors in the power system field to address the optimal integration of PVDG units into DCN [10]. One of the optimization techniques uses metaheuristic algorithms, such as Particle Swarm Optimization (PSO) [11], Crow Search Algorithm (CSA) [12], Heuristic Analysis Based on Regulation [13], Multiverse Optimization Algorithm (MOA) [14], Convex Optimization [15], Vortex Search Algorithm (VSA) [16], Generalized Normal Distribution Optimization (GNDO) [7], and Salp Swarm Algorithm (SSA) [17].

This study examines the impact of using two distinct network types, IEEE 33-bus ACN and DCN, while maintaining the same optimization algorithm, which is the basic PSO for both networks, and the same objective function that consists of minimizing APL and improving the VP. This approach aims to determine the best location and size of the PVDG unit and compare the results obtained.

II. Problem Statement and Constraints

II.1 Objective Function

The basic PSO algorithm aims to identify the optimal location and size of the solar PVDG unit in the proposed IEEE 33-bus ACN and DCN test systems by minimizing the Total Active Power Losses (TAPLs). The following equation represents its formulation [6]:

$$OF = \text{Minimize } \sum_{i=1}^{N_{bus}} \sum_{j=2}^{N_{bus}} TAPL_{i,j} \quad (1)$$

Where :

$$TAPL_{i,j} = \sum_{i=1}^{N_{bus}} \sum_{j=2}^{N_{bus}} APL_{i,j} \quad (2)$$

$$APL_{i,j} = a_{ij}(P_i P_j + Q_i Q_j) + \beta_{ij}(Q_i P_j + P_i Q_j) \quad (3)$$

$$a_{ij} = \frac{R_{i,j}}{V_i V_j} \cos(\delta_i - \delta_j), \quad \beta_{i,j} = \frac{R_{i,j}}{V_i V_j} \sin(\delta_i - \delta_j) \quad (4)$$

Where, $R_{i,j}$ represents the resistance of the line, N_{bus} is the bus number, (V_i, V_j) and (δ_i, δ_j) are the voltages and angles at the buses, respectively. (P_i, P_j) and (Q_i, Q_j) represent active and reactive powers, respectively.

II.2 Power Conservation Constraints

Each bus's active and reactive power injections should match the combined power of the loads connected to that bus [18] :

$$P_G + P_{PVDG} = P_D + APL \quad (5)$$

$$Q_G = Q_D + RPL \quad (6)$$

Where, P_G and Q_G illustrate the total active and reactive powers from the generator, respectively. P_D and Q_D are the load's total active and reactive powers, respectively. APL and RPL represent active and reactive power losses, respectively. P_{PVDG} is the PVDG's output power.

II.3 Distribution Line Constraints

1) Bus Voltage Limits

According to the following equation, the magnitude of the voltage at each bus is constrained by a minimum and a maximum value [19]:

$$V_{min} \leq |V_i| \leq V_{max} \quad (7)$$

2) Voltage Drop Limits

The following formulation can be used to express the voltage drop limits [16]:

$$|1 - V_j| \leq \Delta V_{max} \quad (8)$$

3) Line Capacity Constraint

The following equation states that each distribution feeder's power flow must be compatible with the line's thermal capacity [20]:

$$|S_{i,j}| \leq S_{max} \quad (9)$$

Where, V_{min}, V_{max} represents the minimum and maximum voltage limits, respectively. ΔV_{max} is the maximum voltage drop limit. S_{max} and $S_{i,j}$ are the maximum and apparent power in the distribution line, respectively.

II.4 PVDG Constraints

The boundaries of the PVDG unit are defined by the following expressions [18], [20], [21]:

1) PVDG Capacity Limits

The PVDG capacity should fall between the following ranges:

$$P_{PVDG}^{min} \leq P_{PVDG} \leq P_{PVDG}^{max} \quad (10)$$

$$\sum_{i=1}^{N_{PVDG}} P_{PVDG}(i) \leq \sum_{i=1}^{N_{bus}} P_D(i) \quad (11)$$

2) Position of PVDG Units

Except for the slack bus (bus 1), all buses are eligible for PVDG unit installation as follows:

$$2 \leq PVDG_{position} \leq N_{bus} \quad (12)$$

3) Number of PVDG Units

The allowable number of PVDG units installed in the distribution system that should not be surpassed is limited by a maximum number of units:

$$N_{PVDG} \leq N_{PVDG.max} \quad (13)$$

4) Location of PVDG Units

Each bus can only have one PVDG unit:

$$n_{PVDG,i} / Location \leq 1 \quad (14)$$

Where, P_{PVDG}^{min} and P_{PVDG}^{max} are the minimum and maximum PVDG's output power, respectively. N_{PVDG} is the PVDG unit's number. $n_{PVDG,i}$ is the location of PVDG units at bus i .

III. Particle Swarm Optimization (PSO)

Basic PSO is a population-based metaheuristic optimization algorithm put forward originally by doctors Kennedy and Berhart in 1995 [22]. It was first intended to solve only continuous nonlinear problems; afterwards, further enhancements were applied to tackle a wider range of optimization problems. PSO is inspired by the social behavior of animals like birds and fish in their search for food and prey. It consists of two equations [23]:

1) Velocity Equation

The particles of the swarm move throughout the hyperspace with each other in a certain way where each particle updates its coordinates based on its own best search experience.

$$V_i^{k+1} = \omega \cdot V_i^k + c_1 r_1 [P_{best}^k - X_i^k] + c_2 r_2 [G_{best}^k - X_i^k] \quad (15)$$

Where, V_i is the velocity of the particle, ω is the inertia weight, c_1, c_2 are the acceleration coefficients, r_1, r_2 are independent random numbers, P_{best} is the best-known position of the particle, G_{best} is the best-known position of the entire swarm.

2) Position Equation

In each iteration, the particle with the best solution shares its position coordinates information with the rest of the swarm.

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (16)$$

Where, X_i is the position of the particle.

IV. Test System, Results and Discussion

In MATLAB (version 2021.a), the suggested PSO method was implemented on a laptop computer characterized by an Intel Core i5 microprocessor with an execution speed of 2.6 GHz and a RAM memory of 4 GB. To see the performance of the proposed methods, we resort to an IEEE 33-bus RDN standard as the test system, which consists of 33 buses and 32 distribution line branches with a nominal voltage of 12.66 kV (12.66 kV = 1 p.u.), an active power of 3.715 MW, and a reactive power of 2.300 MVar, as represented in Figure 1.

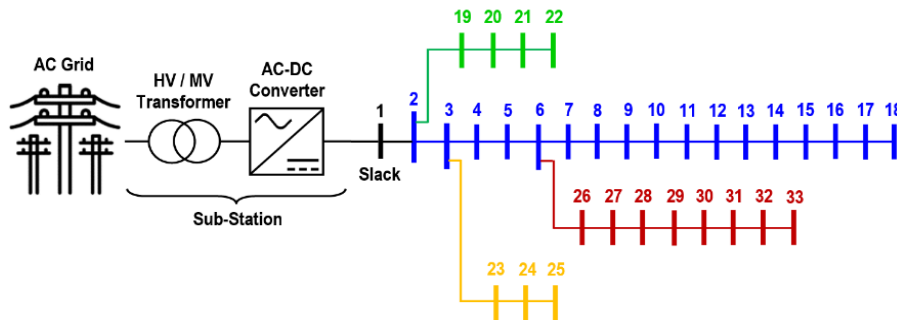


Figure 1. Single line diagram of IEEE 33-bus test distribution system [24].

The PSO algorithm's convergence curves for each of the two networks in the presence of the solar PVDG unit are illustrated in Figure 2. The IEEE 33-bus AC and DC test systems provide their optimal solution after 34 and 12 iterations, respectively; therefore, the DC network converged rapidly, delivering the best value for the objective function (APLs reduction), and the optimal results obtained regarding the location and the size after implementing the aforementioned algorithm were the 7th bus and 2.8554 MW for the ACN and the 6th bus and 2.5152 MW for the DCN, respectively.

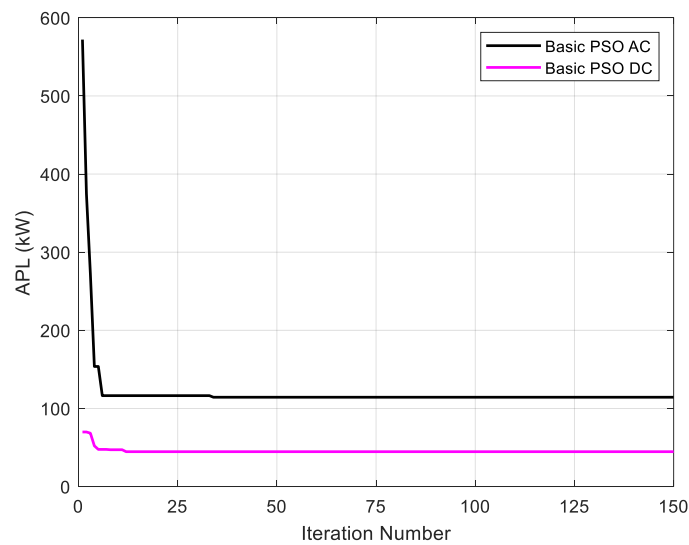


Figure 2. The AC and DC network convergence curves.

Figures 3 and 4 represent the bus VP before and after the implementation of the PVDG unit for both networks. The results obtained in Figure 3 demonstrate that in both cases, the VPs were improved after the integration of the PVDG units into the RDN. In Figure 3, V_{min} equals 0.9038 p.u. for ACN and 0.9247 p.u. for DCN, where the improvement was observed; however, both remain well below the Voltage Deviation (VD) limit of 0.9500 p.u. In Figure 4, it is clear how the voltage profile was improved at all buses in the presence of PVDG, with much superior results for the DCN at 0.9699 p.u. above the VD limit compared with the ACN at 0.9495 p.u.

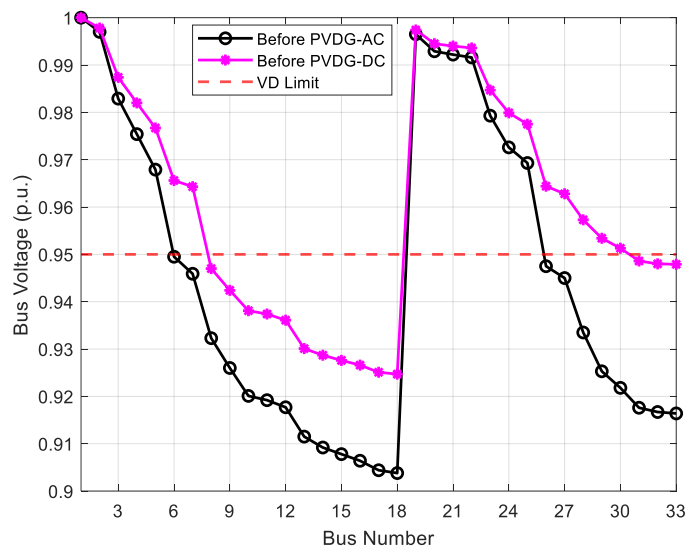


Figure 3. Bus voltage profiles without PVDG.

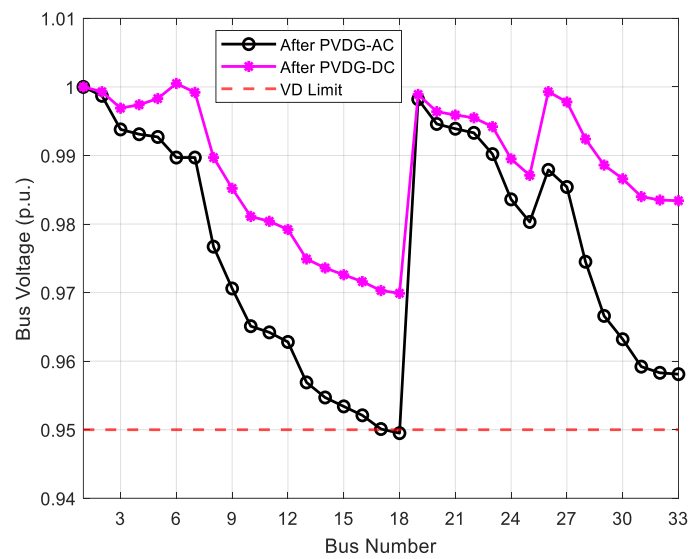


Figure 4. Bus voltage profiles with PVDG.

Figures 5 and 6 represent the active power losses before and after the installation of the solar PVDG unit for both networks. In Figure 5, the APLs' overall values were 135.2582 kW for the DCN and 210.9875 kW for the ACN, and the reduction was observed in all branches with a total average of 35.8927%. The advantage of the DCN was due to the elimination of the reactive power in the lines. In Figure 6, the APL was reduced to much lower values due to the presence of the PVDG, with 44.6952 kW for DCN and 114.3882 kW for ACN. This is related to the identification of the best location and size of the PVDG unit.

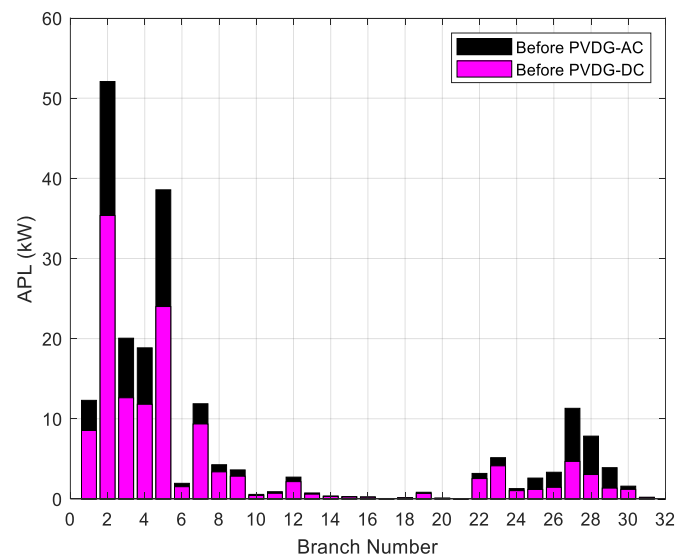


Figure 5. Branch active power losses without PVDG.

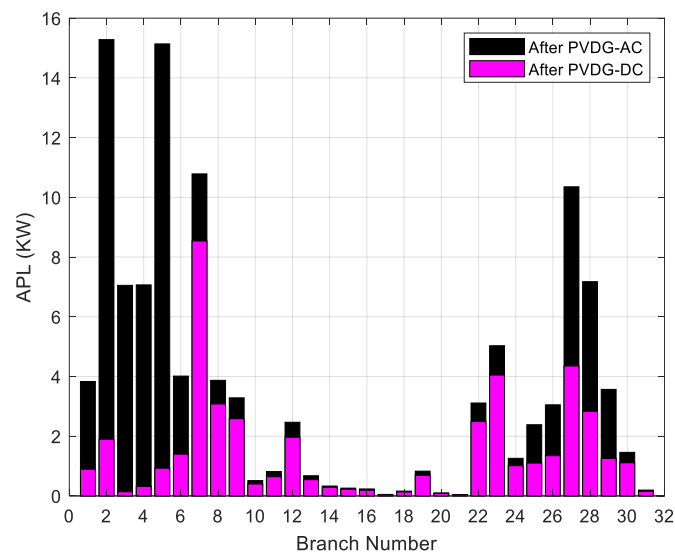


Figure 6. Branch active power losses with PVDG.

Tables 1 and 2 designate the final results obtained, which emphasize the superiority of DCNs over ACNs and the positive effect after connecting the PVDG unit to the grid. The percentage of active power losses' reduction was 66.9556%, and the minimum voltage was 0.9699 p.u. for DCN, compared with 45.7843% and 0.9495 p.u. for ACN, respectively. After comparing the optimization results, the DC network is more suitable for an energy source that delivers direct current, like photovoltaic stations and battery storage systems; thus, by minimizing the power losses, other essential technical, economic, and environmental aspects will simultaneously be minimized as well.

Table 1. Results of ACN and DCN before PVDG integration.

Network type	APL (kW)	$V_{\min}$ (p.u.)
ACN	210.9875	0.9038
DCN	135.2582	0.9247

Table 2. Results of ACN and DCN after PVDG integration.

Network Type	PVDG Parameters		APL (kW)	Δ APL (%)	$V_{\min}$ (p.u.)
	Location (Bus)	Size (MW)			
ACN	7	2.8554	114.3882	45.7843	0.9495
DCN	6	2.5152	44.6952	66.9556	0.9699

V. Conclusion

This study's objective function consisted of minimizing the active power losses and improving the voltage profile using the basic particle swarm optimization algorithm to allocate the solar photovoltaic distributed generator unit in the radial distribution network and determine its size for the IEEE 33-bus test systems before and after the integration while considering both alternative and direct current networks.

The findings of the simulation show that if the PVDG unit was properly allocated and sized in the RDN, the result would be a reduction in the ALPs for all branches and an improvement in the VP in all buses. Therefore, by comparing the two networks, DCN happens to be more effective, ensuring the maximum reduction of ALPs at 66.9556%, compared with 45.7843% for ACN, besides having a better VP.

In conclusion, the replacement of ACNs with DCNs can face financial and technical issues; however, the power distribution companies and the renewable energy industry can collaborate on finding solutions for new networks under construction and take into consideration using DCNs instead of ACNs to connect new photovoltaic stations to the RDN and obtain better-performing electrical networks.

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