Maximum Power Penetration of Distributed Energy Resources with Sizing and Location

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***Abstract*—The motivations for incorporating renewable energy sources into power distribution networks are the diminishing availability of non-renewable energy resources, increasing demand for electricity, and the imperative for clean energy generation. It is important to improve the total capacity of distributed energy resources (DERs) that can be smoothly integrated into a specific feeder without adversely affecting voltage levels, protection mechanisms, power quality, and without requiring feeder upgrades or modifications. However, the escalating injection of DERs into the network may lead to operational challenges, including voltage fluctuations, reverse power flow, power quality issues, and thermal overloading of distribution lines, among others. This study presents an optimization technique for efficient incorporation of DERs into a distribution system. Here, a particle swarm optimization (PSO)-based algorithm is developed for the maximum penetration of DERs not for the only optimal size but also their location in the power system. We employ the Newton-Raphson load flow method to analyze power flow, considering major constraints such as overvoltage, undervoltage, and ampacity. The bus voltages were significantly improved after the penetration of three DER units in the system. The analysis is validated through MATLAB/Simulink simulation using the IEEE-33 bus distribution system as a testbed.**

***Index Terms*—Distributed energy resources, Newton-Rapson load flow, Particle swarm optimization.**

I. INTRODUCTION

In recent years, the integration of distributed energy resources into traditional power systems has garnered significant attention due to their potential to enhance network reliability, reduce carbon emissions, and increase energy efficiency. Encompassing a diverse range of energy generation and storage technologies located close to the point of consumption, DERs include solar photovoltaics (PV), wind turbines, battery energy storage systems (BESS), and micro-turbines, among others. The base load is growing exponentially as a result of the increasing daily need for electricity due to population growth. The key contributing to closing the gap between generation and demand is mainly the integration of DERs into the power networks. Providing precise voltage profiles and high-quality power to bridge the gap between supply and demand in the twenty-first century is the top goal.

The deployment of DERs plays a pivotal role in the transformation of traditional power distribution systems into active distribution networks [1]. To the utilities as well as consumers, DERs offer various benefits in technologies, economy and the environment. Their key technological advantages include power loss minimization, improved voltage control and power quality, improved system stability and loadability, reduced transmission and distribution networks, as well as enhanced overall energy efficiency [2]. Ecologically and economically, the penetration of DERs involves benefits in saving world fossil fuels and reducing emissions, but with the tradeoffs of raising transmission and distribution costs and rising market prices for electricity. Bedises, excessive penetration of DERs may cause several operational problems if not properly connected to the distribution networks. Indeed, extra power from DERs may exacerbate the reverse current, which causes voltage increase and heat overload problems. An increasing number of operational problems, including overvoltage, reverse power flow, thermal overload and power quality problems may also arise from increasing solar power injection (PV) into to the network [3]. As such, obtaining the best strategy towards maximum power penetration of DERs given practical constraints of power distribution networks and requirements of power quality remains an open question.

Optimizing the deployment of DERs involves the allocation of power capacity and placement of DERs to not only maximize their active power contribution but also identify the optimal locations for installation. An optimization and energy management strategy was proposed in [4] using a particle swarm optimization (PSO) algorithm to decrease the operational costs of a hybrid residential microgrid with a diesel engine, wind turbine, solar array, and battery energy storage system. The claimed results include minimal costs of DERs, decreased CO2 emissions, and enhanced penetration level. For the management of distributed energy (DG) in smart buildings, an algorithm based on dynamic demand response was proposed in [5] to balance between energy consumption and production by regulating predefined user load patterns.

By incorporating optimal power flow in the analytical approach, a multistage algorithm was developed in [6] to evaluate the hosting capacity of DERs in a distribution system within its operational limits. Heuristic methods, genetic algorithm (GA), and PSO were utilized in [7] for the optimal placement of renewable DG units to minimize annual energy losses and voltage deviation indices, ensuring uninterrupted power supply to users. To optimize the placement and capacity of distributed generation units, a GA was also used in [8] with the goal of minimizing network losses while respecting voltage and harmonic constraints. The impact of network configuration on maximum load capacity and permissible DG integration was investigated in [9] for distribution systems to identify the optimal penetration level by using the normalized impact factor score approach.

The problem of optimizing both distributed renewable energy and storage investments (sizing and siting) was tackled in [10] by rendering a bilevel optimization program into a mixed integer linear programming algorithm. Recently, a virtual power plant was proposed in [11] using a DG optimum scheduling to solve the problem of high penetration of renewable DERs under practical conditions of inherent intermittency and uncertainty in their output power via temporal decoupling of the charging and discharging model of energy storage systems. For power distribution systems with high penetration of renewable DERs, an extended continuation power flow method was proposed in [12] for static voltage stability assessment taking into account dynamic characteristics of synchronous generators and renewable power generation.

In this study, we introduced a PSO-based algorithm designed to optimize DER placement and power capacity by leveraging spatial analysis, aiming to maximize the size of DERs while adhering to constraint limits. The algorithm considers both single and multiple bus configurations in the power distribution system, ensuring that the optimal placement and capacity of DERs are achieved within the constraints and location-specific requirements. The Newton-Raphson load flow method is used with a Jacobian matrix to analyze power flow subject to major constraints such as overvoltage, undervoltage, and ampacity. As a result, our approach can support the maximum penetration of DERs while overcoming issues affecting power quality and voltage efficiency to assist stakeholders for a cost-effective and energy-sustainable solution. The proposed methodology, developed and tested through MATLAB coding, is validated against the standard IEEE-33 bus distribution system.

II. SYSTEM DESCRIPTION

The IEEE-33 bus radial system consists of 33 nodes, a total of 37 lines, 32 loads, 32 PQ buses, one feeder, and one slack bus. The system operates with 32 closed switches and 5 open switches. The power supply source is located at bus 1, which maintains a constant voltage of 12.66 kV. All loads are assumed to be constant, with active and reactive power values of 3715 kW and 2300 kVAr, respectively. The line, load data of the IEEE-33 bus distribution system is taken from [13]. The standard IEEE-33 bus distribution network is shown in Fig 1.

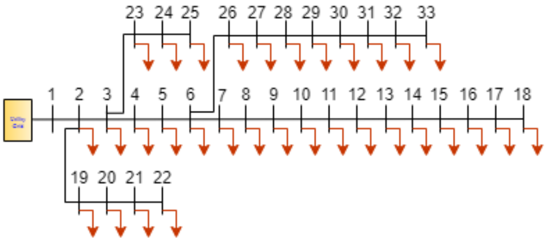

Fig. 1. IEEE-33 bus 33 bus distribution system

A. DER Formulation- Photovoltaics

Photovoltaics (PV) are one of renewable energy sources that directly convert sunlight radiation into electrical energy. The amount of solar radiation that photovoltaic systems receive affects their power output [5]. Here, three PV units are employed at first as DERs. They are assessed using load flow calculations on the IEEE-33 bus test system. Because the power system and AC load flow present a non-linear model, the optimization involved falls within the category of mixed-integer non-linear programming (MINLP). The output power of the PV system is given by:

$$P_{pv} = \eta_{pv} N_{pv} P_{mpv} \frac{G_t}{G_{STC}}, \tag{1}$$

where η_{pv} is the system efficiency, N_{pv} is the number of PV modules, P_{mpv} is the rated power of a single PV module (usually given in watts), G_t is the total incident irradiance from sunlight onto the PV system, and G_{STC} is the solar irradiation under typical test circumstances (T=25°C, usually 1000 W/m²).

B. DER Formulation- Other renewable energy sources

In addition the PV arrays, other renewable energy sources can include wind turbines (land-based or offshore), biomass, solar thermal, geothermal, small hydro turbines, and electrochemical devices like fuel cells. Energy storage systems can be considered as a special type of non-conventional DERs, for example, battery energy storage systems, flywheel, superconducting magnetic energy storage, compressed air energy storage, and pumped storage [13]. Most popular among those renewables are perhaps the wind energy, for which the output power for a wind turbine is given as,

$$P_w = C_{pw}(\frac{1}{2}\rho_w A_w v_w^3), \tag{2}$$

where ρ_w is the air density, A_w is the rotor swept area, v_w is the wind speed, and C_{pw} is the wind power coefficient.

III. PROBLEM FORMULATION

The primary objective is to maximize the total active power penetrated from DERs corresponding to the highest level or threshold at which DERs, such as solar photovoltaics, wind turbines, energy storage systems, and demand response technologies, can be integrated into a specific power system or grid without causing significant operational or stability issues. The total capacity of installed DERs is the summation of all installed DER units in all buses of the IEEE-33 bus test system, which can be calculated as,

$$\max_{Z} \sum_{i=1}^{n} P_i^{inj,DER}, \tag{3}$$

where Z represents the decision variables, n is the number of buses and $P_i^{inj,DER}$ represents the active power injected from distributed energy resources from all bus $j, j = 1, .., n; j \neq i$ to bus i of the distribution system. Figure 2 illustrates a typical particle to be used in the PSO algortihm for solving the above optimization problem. The particle consists of two parts. Each dimension in part 1, $\{S_1, S_2, ..., S_{\text{Num}}\}$, represents the size of the corresponding DERs (in MW) within its specified bounds. Part 2, $\{L_1, L_2, ..., L_{\text{Num}}\}$, represents the location of the DERs.

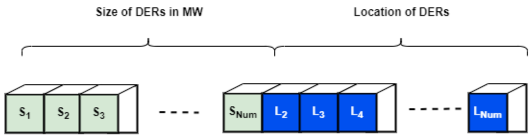

Fig. 2. Configuration of a PSO for the proposed problem

A. Decision Variables

The objective of the optimization problem is to simultaneously determine the optimal sizes and locations of DER in the IEEE-33 bus test system. Therefore, the decision variables Z for this optimization problem are defined as,

$$Z = \left[\overbrace{(S_1, S_2, S_3, \ldots, S_{\text{Num}})}^{\text{Size of DERs}}, \overbrace{(L_2, L_3, L_4, \ldots, L_{\text{Num}})}^{\text{Location of DERs}}, \right]. \tag{4}$$

The size variables S are expressed per unit (p.u.) of the system base in MW correspondingly with specific upper and lower bounds. The location variables represent the bus locations where the candidate DGs will be installed.

B. Constraints

The system variables involved in the optimization are subjected to the following constraints:

$$V_{min} \leq V_i \leq V_{max}, \tag{5}$$

$$I_{min} \leq I_i \leq I_{max}, \tag{6}$$

$$P_{min}^{DER} \leq P_i^{DER} \leq P_{max}^{DER}, \tag{7a}$$

$$Q_{min}^{DER} \leq Q_i^{DER} \leq Q_{max}^{DER}, \tag{7b}$$

$$n_{loc,min} \leq DER_{loc} \leq n_{loc,max}, \tag{8}$$

where V_{max} and V_{min} denote respectively the maximum and minimum values permitted for voltage V_i, values I_{min} and I_{max} are the lowest and greatest acceptable current I_i, values P_{min}^{DER} and P_{max}^{DER} are the lowest and highest acceptable active power P_i^{DER}, values Q_{min}^{DER} and Q_{max}^{DER} are the lowest and highest acceptable reactive power Q_i^{DER}, and $n_{loc,min}$ and $n_{loc,max}$ represent respectively the position of DERs from the smallest and largest values among the nodes of the network.

IV. LOAD FLOW ANALYSIS

The injection of active power P_i and reactive power Q_i of the distributed system at bus i are obtained as the difference of the relevant powers generated P_{Gi} and Q_{Gi} with respect to the load powers P_{Li} and Q_{Li}. They can also be derived from the phasor analysis for the complex power at bus i, given the admittance $G_{ij} + jB_{ij}$ between node i and j of the network. As such, the equations for the active and reactive power injections at bus i from DERs at all nodes can be written as,

$$P_i = P_{Gi} - P_{Li}, \tag{9a}$$

$$P_i = \sum_{j=1}^{n} V_i V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right), \tag{9b}$$

$$Q_i = Q_{Gi} - Q_{Li} \tag{10a}$$

$$Q_i = \sum_{j=1}^{n} V_i V_j \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij} \right), \tag{10b}$$

where V_i and V_j are the magnitude of the voltages at node i and j, respectively, G_{ij} represents conductance and B_{ij} is susceptance between nodes i and j, angle $\theta_{ij} = \theta_i - \theta_j$ is the phase difference between voltage phasors at node i and j.

Let us denote ΔP_i and ΔQ_i respectively the change in active power and reactive power at node i. They can be obtained as the differences between the generated active power P_{Gi} and the load active power P_{Li}, taken away the active power P_i and reactive power P_i injected to node i from all the DERs at node i and the remaining resources. We have

$$\Delta P_i = P_{Gi} - P_{Li} - V_i \sum_{j=1}^{n} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right). \tag{11}$$

$$\Delta Q_i = Q_{Gi} - Q_{Li} - V_i \sum_{j=1}^{n} V_j \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij} \right). \tag{12}$$

By taking the partial derivatives of equations (11) and (12), we obtain the Jacobian matrix $J = [J_{ij}], i, j = 1, ..., n$ for the whole network.

The diagonal entries $J_{ii} = \begin{bmatrix} H_{ii} & N_{ii} \\ M_{ii} & L_{ii} \end{bmatrix}$ are determined as,

$$H_{ii} = \frac{\partial \Delta P_i}{\partial \theta_i} = V_i \sum_{j=1}^{n} V_j \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij} \right), \tag{13a}$$

$$N_{ii} = \frac{\partial \Delta P_i}{\partial V_i} = - \sum_{\substack{j=1 \\ j \neq i}} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) - 2 V_i G_{ii}, \tag{13b}$$

$$M_{ii} = \frac{\partial \Delta Q_i}{\partial \theta_i} = -V_i \sum_{j=1}^{n} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right), \tag{13c}$$

$$L_{ii} = \frac{\partial \Delta Q_i}{\partial V_i} = -\sum_{\substack{j=1\\ j\neq i}} V_j \left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right) + 2V_iB_{ii}. \tag{13d}$$

The off-diagonal ($j \neq i$) entries $J_{ij} = \begin{bmatrix} H_{ij} & N_{ij} \\ M_{ij} & L_{ij} \end{bmatrix}$ are determined as,

$$H_{ij} = \frac{\partial \Delta P_i}{\partial \theta_j} = -V_iV_j \left(G_{ij}\cos\theta_{ij} - B_{ij}\sin\theta_{ij}\right), \tag{13e}$$

$$N_{ij} = \frac{\partial \Delta P_i}{\partial V_j} = -V_i \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right), \tag{13f}$$

$$M_{ij} = \frac{\partial \Delta Q_i}{\partial \theta_j} = V_iV_j \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right), \tag{13g}$$

$$L_{ij} = \frac{\partial \Delta Q_i}{\partial V_j} = -V_i \left(G_{ij}\cos\theta_{ij} - B_{ij}\sin\theta_{ij}\right). \tag{13h}$$

The Jacobian matrix J is required for solving power flow equations numerically by using the Newton-Raphson method. It represents the sensitivity of power mismatches (ΔP and ΔQ) concerning the changes in voltage magnitude and phase angle. Consequently, the percentage improvement representing the relative increase of voltage after improvements with optimization and expressed in %, can be calculated as,

$$V_{inc} = \left(\frac{\textit{Final Voltage} - \textit{Initial Voltage}}{\textit{Initial Voltage}}\right) \times 100. \tag{14}$$

The per-unit minimum voltage, U_{min}, is defined as:

$$U_{\text{min}} = \frac{\min V_i}{V_{\text{nom}}}, \tag{15}$$

where $\min V_i$ represents the minimum voltage observed at any node in the system, and V_{nom} is the nominal or reference voltage of the system. This metric provides a normalized measure of the lowest voltage level relative to the system's nominal voltage.

For the power system to maintain stability and remain insensitive to peak loading conditions, it is crucial that $U_{\text{min}} < 1$ is kept as close to 1 as possible. This ensures that the minimum voltage in the system does not drop excessively below the nominal value to ensure that the system can handle peak loads effectively without significant voltage drops, thus promoting reliable and efficient power distribution and preventing potential voltage sags that could lead to operational issues or equipment damage.

V. PSO-BASED ALGORITHM FOR OPTIMAL PENETRATION

In this study, we approach the optimization problem using a meta-heuristic technique based on the PSO. As a global optimization method, PSO has garnered significant attention from researchers over the past two decades due to its simplicity in handling complex, multidimensional problems that are challenging for deterministic algorithms to solve. Inspired by the social behaviors observed in bird flocking and fish schooling, PSO involves particles that, at each step, utilize their behaviours from previous iterations. Each particle updates its position based on both its own best-known position and the best-known positions of its neighbors in the search space [14], [7]. In a D-dimensional search space, the particles seek optimal values by updating their positions based on both their own experiences and the experiences of neighboring particles. The process ends at some termination condition to yield the global optimal solution. Widely applied in many optimization problems in engineering, PSO has shown to be an effective approach for our purpose here since it can manage well the uncertainties brought on by the frequent parameter changes of the distribution system.

Algorithm 1 PSO for Maximum Penetration of DERs

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Input: PSO Parameters: $LB$, $UB$, $c_1$, $c_2$, $w_{\text{max}}$, $w_{\text{min}}$, $max_{ite}$, $n$ (number of particles), $m$ (number of variables)
Input: System Parameters: Line data, load data
Begin:
Initialize particle positions $X$
Initialize particle velocities $U$
Load Flow Calculation:
Perform Newton-Raphson load flow method as in Eqs. (9a-13h)
Calculate DER penetration, voltage, and current as in Eqs. (3-5)
Evaluate Initial Fitness:
Main PSO Loop:
for each particle $i$ from 1 to $n$ do
    Update velocity $U$ as in Eq. (16a)
    Update position $X$ as in Eq. (16b)
    Evaluate Fitness:
    Check all constraints and number of iterations as in Eqs. (5-8)
    Update Personal Bests and Global Best
end for
Output: Maximum size and location of DER
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Let the current position and velocity of the N-particle swarm be respectively X^t and U^t, where t is the iteration $t = 1, 2, ..., n_{\text{iter}}$. The particle velocity is updated using the motion equation below:

$$U^{t+1} = wU^t + c_1r_1(P_{best}^t - X^t) + c_2r_2(G_{best}^t - X^t), \tag{16a}$$

where w is the inertia weight with $w \in [w_{min}\ w_{max}]$, c_1 and c_2 are the acceleration coefficients, r_1 and r_2 are random numbers distributed in [0 1], and P_{best} and G_{best} are repectively the personal best and global best. The particle position is updated with the new velocity as,

$$X_k^{t+1} = x_k^t + \chi(v_k^{t+1}), \tag{16b}$$

where χ is a rate coefficient. In PSO, a randomly generated population is used as the starting point and a proper parameter setup is crucial to the overall performance. Table I presents the control parameters of our PSO algorithm as well as the system constraints.

The maximization for the objective function (3), which is the PSO fitness, subject to constraints (5-9) is proceeded with the PSO algorithm described

TABLE I
PSO CONTROL PARAMETERS AND SYSTEM CONSTRAINTS

Parameter	***Symbol***	***Value***
Number of iterations	n_{iter}	100
Number of particles	N	100
Number of variables	L_l	2
Acceleration coefficients	C_1 and C_2	2
Random values	r_1 and r_2	between 0 and 1
Minimum inertia weight	$w_{\min}$	0.4
Maximum inertia weight	$w_{\max}$	0.9
Rate coefficient	χ	1
Lower boundary for DER	L_{B}	0
Upper boundary for DER	U_B	5
Lower boundary for buses	L_B	2
Upper boundary for buses	U_B	33

above. After initialization, the updates for the swarm velocity and position (15) are performed with load flow analysis for (9-10) obtained by incorporating the Newton-Raphson method wherein the Jacobian matrix is determined in (13). The process is conducted till the termination after n_{iter} iterations. The global best fitness is eventually considered the maximal active power of all installed DERs under practical constraints and the optimal solution for the size and location of DERs is recorded correspondingly. Algorithm 1 shows the illustration of the proposed optimization algorithm for maximal penetration of DERs.

VI. RESULTS AND DISCUSSION

The PSO algorithm was applied to the IEEE-33 bus radial distribution system to investigate the maximum penetration of DERs. The peak load consumption of the distribution system was 3715 kW and 2300 KVAr. The minimum voltage at bus 18 was 0.9037 pu. We considered cases of penetration at a single bus and multiple buses. As a result of our optimal placement, it was shown the location of DER1 to be installed at bus 6; DER1 and DER2 at buses 6 and 3; and DER1, DER2, and DER3 at buses 6, 3, and 19, respectively. In terms of capacity allocation, a DER rated at 4.8095 MW was placed at bus 6 in the single DER scheme. For the two-DER scheme, two DERs rated at 4.8095 MW and 1.6856 MW were installed at buses 6 and 3, respectively. For the multi-bus scheme, three DERs with ratings of 4.8095 MW, 1.6856 MW, and 1.4816 MW were installed at buses 6, 3, and 19, respectively. The results were listed in Table II. As it can be seen, the DER integration reduced the net electricity drawn from the substation or main grid by injecting active power locally. Consequently, the integration of three DERs enhanced bus voltage was 0.9799 p.u. at bus 18. The bus voltage improved by 8.44% following the DERs integration. Figures 3 and 4 show respectively the voltage profiles of the IEEE-33 system and the DERs capacity.

A. Comprarative Analysis

To compare with another DER penetration tested on a similar IEEE 33-node standard distribution network, the author considered multiple cases for optimal placement of renewable DG units to minimize annual energy losses and voltage deviation indices for only two DERs [7].

For a fair comparison, we evaluated the best-penetrated combination of the capacities of two DG units under similar load scenarios and compared the sizes of the DG units with voltage profile improvement. In their study, the optimal penetration involved placing two DERs at locations 32 and 6, with a total capacity of 3166.1 kVA and a minimum voltage of 0.964 pu. However, our study integrated two DERs at locations 6 and 3, with a total capacity of 6495.1 kVA and a minimum voltage of 0.9791 pu. This represents an increase in penetration level from 3166.1 kVA to 6495.1 kVA, which is increased by approximately 105.2%. Furthermore, their study reported a voltage level improvement of approximately 5.54%, whereas our approach achieved an improvement of 8.44%, which is shown in Table III.

B. Discussion

Deploying DER systems plays a crucial role in electricity production, enabling the delivery system to handle high loading, reduce losses, and improve voltage profiles. The results obtained indicate that identifying the maximum penetration of the DERs by using optimal size and location in a radial distribution system is thus important for improving the power quality. The results obtained with our PSO-based technique indicated that the maximum penetration of DERs considering their location and size can enhance the bus voltage levels.

Here, particle swarm optimization enables effective exploration of the entire solution space, which effectively helps in identifying the optimal placement and sizing of DERs. Requiring minimal parameter tuning compared to other optimization methods, PSO is sufficiently flexible to adapt to various DER integration scenarios. In addition, the ability to parallelize PSO makes it suitable for large-scale systems with numerous DERs, further enhancing its scalability and performance. One prominent disadvantage of PSO rests with diversity of the particles, causing it being trapped in local optima. To overcome this issue, our work is under progress to incorporate an optimal techique for balancing between exploration and exploitation as well as to consider additional renewable energy resources subject to practical constraints.

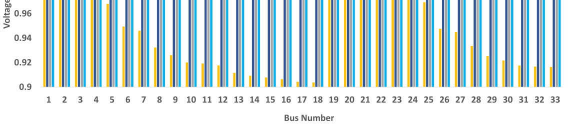

Fig. 3. Voltage profiles of IEEE-33 bus system with DERs

TABLE II
MAXIMUM PENETRATION OF DERS VIA UNIT PLACEMENT

Description	***Base System***	**DER1**	**DER1 and DER2**	**DER1, DER2 and DER3**
Maximum DERs Penetration (MW) & Location		4.8095 & 6	4.8095 & 6 1.6856 & 3	4.8095 & 6 1.6856 & 3 1.4816 & 19
V_{inc} (%)		7.65	8.35	8.44
U_{min} & Location	0.9037 & 18	0.9728 & 18	0.9791 & 18	0.9799 & 18

TABLE III
COMPARISON OF METHODS FOR 2 DG PLACEMENTS

Description	***Heuristic Method [7]***	***Proposed Method***
DER Locations	32, 6	6, 3
Total Capacity (kVA)	3166.1	6495.1
Capacity Improved (%)		105.2
U_{min}	0.964	0.9791
V_{inc} (%)	5.54	8.35

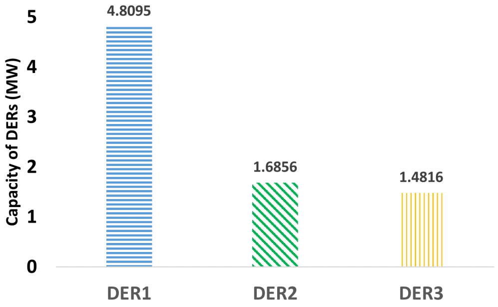

Fig. 4. Capacity of the distributed energy resources

VII. CONCLUSION

The integration of Distributed Energy Resources presents a transformative opportunity to enhance the efficiency, resilience, and sustainability of power systems. For this, advanced optimization techniques play a crucial role in achieving those objectives, enabling the efficient utilization of distributed resources while meeting the evolving needs of modern power systems. In this paper, we have presented a particle swarm optimization-based technique to maximize the penetration of DERs into a distribution system, considering both size and location of the resources penetrated at a single bus as well as multiple buses. The voltage profiles were shown to be significantly improved after the maximum injection of DER into the system. The percentage voltage improvement reached 8.44% after the maximum penetration of three DERs in the IEEE-33 bus test system. Given the promising results, efforts devoted to the development of more effective techniques for further adressing the optimization challenges associated with DER deployment, including renewable energy sources integration, energy storage management, demand response, and grid stability, will unlock full potential of decentralized energy generation can and pave the way towards a more sustainable and resilient energy future.

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