Impact of Load Flexibility on Photovoltaic Hosting Capacity in Distribution Networks

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***Abstract*— In the past fifteen years, power plants utilizing renewable energy sources have played a dominant role within the power sector of European countries. Technical challenges, such as voltage profiles, line capacities, and transformer loadings, impose strong limitations on the maximum installed capacity of renewables in power systems. To address this issue, various novel approaches can be considered to increase the hosting capacity of distribution networks for renewables. This paper introduces a methodology for calculating the impact of demand flexibility on the hosting capacity of distribution networks for photovoltaic (PV) dispersed generation. Specifically, a decomposition of the load flow on each branch of the network is performed to determine the impact of load flexibility on branch loading and bus voltage magnitude. The algorithm's advantage lies in its ability to enhance the distribution network's PV hosting capacity without the need for investments in network element reinforcement.**

***Index Terms*— demand-side response, distribution network, genetic algorithm, hosting capacity.**

I. INTRODUCTION

As the penetration of renewable energy sources (RES) increases, understanding and enhancing network hosting capacity becomes crucial for facilitating the transition to a sustainable energy future. The maximum installed capacity of RES in power systems is limited by technical challenges, such as voltage profiles, line capacities, and transformer loadings [1]. Demand-side response (DSR) emerges as a viable strategy for increasing hosting capacity by actively managing demand to match supply variations. The synergy between hosting capacity and DSR lies in their complementary roles within the power grid. By leveraging DSR mechanisms, such as load shifting, consumers can align their energy usage with periods of abundant renewable generation, effectively reducing node voltage violations and line thermal violations. This optimized load management enhances the effective utilization of existing infrastructure, allowing for greater integration of RES without necessitating extensive grid upgrades.

Numerous papers have investigated this topic, reflecting its significance and complexity within the field. In [2], the authors examined hosting capacity by utilizing hourly load data acquired from rooftop PV panel output. Using MATLAB they simulate the fluctuating PV production and load variability. Notably, the authors restricted their analysis solely to rooftop PV panels and did not consider other RES or network parameters. Furthermore, the proposed approach requires conducting a substantial number of power flow simulations, in order to accurately account for voltage and power constraints. The authors in [3] used genetic algorithm (GA) to evaluate the maximum hosting capacity of a distribution network (DN), examining the influence of bus voltage limitation, transformer and lines thermal limitation on the maximum hosting capacity. In [4], the authors obtained the maximum hosting capacity in a DN considering demand-side management and network reconfiguration, but with predefined location of the RES. In [5], the authors take into consideration the location to which the DER will be integrated, using optimal power flow (OPF) analysis, which requires substantial computation time.

In summary, existing studies considered power flow analysis for obtaining the optimal location of DER and maximum hosting capacity in DN, and they consider all loads in demand-side management (DSM) for enhancing DN hosting capacity, although not all loads have impact on the node or line constraining the hosting capacity. Under this context, this study provides a novel method for DER allocation for maximizing hosting capacity of a DN. The proposed method also introduces selection of loads that have impact on the node or line constraining the hosting capacity of the DN and envisages implementation of DSR programs only on those loads.

The rest of this paper is organized as follows: Section 2 describes the methodology for maximum hosting capacity calculation and selection of loads for participating in DSR. Section 3 demonstrates the proposed methodology on a test model and analyzes the results, while Section 4 summarizes this study.

II. METHODOLOGY

In this paper, a methodological framework aimed at selectively engaging loads in DSR programs to maximize the

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hosting capacity of DNs is introduced. The methodology comprises three distinct stages:

- Stage I: Utilizing GA techniques to determine the optimal location and maximum power output of the PV plant.
- Stage II: Utilizing Z bus matrix analysis to identify load, usually in close electrical proximity to critical nodes or lines within the network, which can potentially participate in DSR initiatives.
- Stage III: Employing GA methodologies once more to determine the optimal load shifting strategies that yield maximal enhancements to the hosting capacity of the DN.

The forthcoming subsections of this paper provide detailed explanations of each stage described above.

A. Location and Maximum Power Output of PV Plant Without DSR

In Stage I, the location and maximum capacity of the PV plant is determined using GA. To mitigate the computational burden associated with subsequent load flow calculations during the optimization, a novel methodology for assessing node voltages and line loadings is employed. This approach, based on [6], notably decreases computational complexity by requiring only single load flow calculation, performed when no DG are connected to the DN.

1) Voltage and Current calculations

Through load flow analysis, by specifying the impedance of the branches $\underline{Z}_j = R + jX$ and the load at each node, the receiving complex power $\underline{S}_j = P_j + jQ_j$ and percentage voltage v_j at the *j-th* node are obtained. Upon integrating the DG into the system, considering constant load at each node, power from the DG begins to flow to nodes that are electrically near the DG. This results in a reduction of power import from the network and a decrease in loading on the branches directly connecting the DG to the reference bus. The loading of each branch connecting the DG and the reference bus is reduced by the power output of the DG, giving the effect that the entire DG power is directed to the reference bus, as shown on Fig 1.

The power flow through each branch $\underline{S}_j^N$ after DG integration at node *i* can be calculated as:

$$\underline{S}_j^N = \begin{cases} \underline{S}_j & if\ j\ is\ not\ incident\ to\ i \\ \underline{S}_j - \underline{S}_{DGi} & otherwise \end{cases} \quad (1)$$

In a scenario with multiple DG, the power flow through each branch can be calculated as:

$$\underline{\mathbf{S}}_j^N = \underline{\mathbf{S}}_j - \mathbf{I} \cdot \underline{\mathbf{S}}_{DG} \quad (2)$$

where $\underline{\mathbf{S}}_j^N$ is a vector of the power flow through each branch after DG integration, $\underline{\mathbf{S}}_j$ is a vector of the power flow through each branch before DG integration, $\underline{\mathbf{S}}_{DG}$ is the complex power generated from the DGs at each node, and $\mathbf{I}$ is a (0, 1) matrix with dimension number of lines x number of nodes, and is formulated as:

$$\mathbf{I} = \begin{cases} 1 & if\ branch\ j\ is\ incident\ to\ node\ i \\ 0 & otherwise \end{cases} \quad (3)$$

The change in loading of lines will also change the voltages of the nodes. In a radial medium voltage distribution network, the voltage drop across a line can be calculated as:

$$\Delta v_{j\%} = \frac{100}{Un^2}(P_j R_j + Q_j X_j) \quad (4)$$

After integrating the DG, the new voltage v_j^N can be calculated as:

$$v_j^N = v_0 - \frac{100}{Un^2} \sum_{i \in \mathbf{B}} P_i^N R_i + Q_i^N X_i \quad (5)$$

Substituting (2) into (5), we obtain:

$$\begin{aligned} v_j^N &= v_0 - \frac{100}{Un^2} \sum_{i \in \mathbf{B}} (P_i - \mathbf{I}_{ji}\mathbf{P}_{DG})R_i + (Q_i - \mathbf{I}_{ji}\mathbf{Q}_{DG})X_i \\ v_j^N &= v_0 - \frac{100}{Un^2} \sum_{i \in \mathbf{B}} P_i R_i + Q_i X_i + \frac{100}{Un^2} \sum_{i \in \mathbf{B}} \mathbf{I}_{ji} P_{DG} R_i + \mathbf{I}_{ji} Q_{DG} X_i \\ v_j^N &= v_j + \frac{100}{Un^2} \sum_{i \in \mathbf{B}} \mathbf{I}_{ji} P_{DG} R_i + \mathbf{I}_{ji} Q_{DG} X_i \end{aligned} \quad (6)$$

where $\mathbf{B}$ is a vector containing the branches that are incident to node *j*, and $\mathbf{I}_{ji}$ is the value of the j-*th* row and i-*th* column of $\mathbf{I}$.

In a distribution network with multiple DGs, the voltage v_j^N at each node can be calculated as:

$$\mathbf{v}^N = \mathbf{v} + \frac{100}{Un^2} \begin{bmatrix} \mathrm{Re}\{\underline{\mathbf{Z}}\} \cdot (\mathbf{I} \cdot \mathrm{Re}\{\underline{\mathbf{S}}_{DG}\}) + \\ \mathrm{Im}\{\underline{\mathbf{Z}}\} \cdot (\mathbf{I} \cdot \mathrm{Im}\{\underline{\mathbf{S}}_{DG}\}) \end{bmatrix} \quad (7)$$

Now, the current through branch j can be calculated as follow:

$$I_j = \frac{S_j}{\sqrt{3} \cdot \frac{U_n}{100} v_j} \quad (8)$$

The GA implemented in this stage serves as a powerful optimization tool aimed at determining the optimal location and maximum capacity of the PV plant within the DN.

Through iterative generations of individuals, each subjected to evaluation and genetic manipulation inspired by biological evolution, the algorithm converges towards configurations that maximize PV capacity without violating voltage and current limitations, for nodes and lines, respectively. The methodology described previously enables this GA framework to efficiently calculate the nodes voltage and lines loading, enabling structured but random search for configurations of PV installations in a manner that satisfies technical constraints and maximizes the network's hosting capacity.

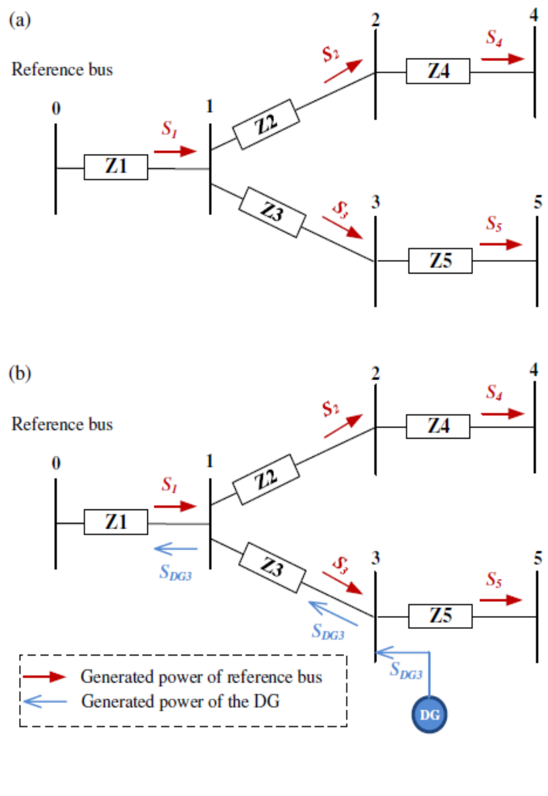

Figure 1. Example of a distribution network.
(a) Wthout DG; (b)With DG at node 3

In this stage, each individual in the population of the GA possesses a number of genes corresponding to the total number of nodes within the DN. Each gene encodes the capacity of the integrated PV plant at its respective node. The fitness function employed in this GA leverages equations (7) and (8) to evaluate and select the optimal solution that satisfy node voltage constraints and line current capacities. While this GA framework is capable of determining the optimal capacity and placement for multiple PV plants, the scope of this paper is limited to the optimization of a single PV plant.

B. *Loads Selection for Demand Side Response*

The main idea of this paper revolves around this stage, which stands as the foundational pillar of the proposed methodology. Building upon the outcomes derived from Stage I GA analysis, stage II obtains the voltage or current profiles associated with the node or line that constrain the hosting capacity of the DN. Afterwards, based on the network topology, the *Z* bus matrix is formed. This matrix enables the computation of parameters that give information about the electrical distance between nodes and branches within the network. Those parameters are obtained as following:

$$a^{i}_{jk} = (z_{ji} - z_{ki})y_{jk} + z_{ji}y^{sh}_{jk} \tag{9}$$

where y_{jk} and y^{sh}_{jk} are the series and shunt admittance of the π equivalent circuit of the line, z_{ji} and z_{ki}, the *ji* and *ki* element of the Z_{bus} matrix, and a^{i}_{jk} is a parameter associated with the electrical distance between branch *jk* and node *i*. The construction of the a^{i}_{jk} matrix is based on [7, 8]. Using the numerical values of the parameters a^{i}_{jk} in the matrix, loads situated in close electrical proximity to the node or line constraining the hosting capacity is identified and are selected for participation in demand response initiatives. This strategic selection process, focusing on loads with the greatest impact on the hosting capacity constraints, also optimizes resource allocation for demand response measures. It is important to acknowledge the variability in the influence of different loads on the hosting capacity constraints, emphasizing the significance of a targeted approach in increasing the efficiency of demand response strategies. By selectively engaging loads, the proposed methodology not only enhances the hosting capacity of the DN, but also reduces the expenditures associated with participation of loads in demand response.

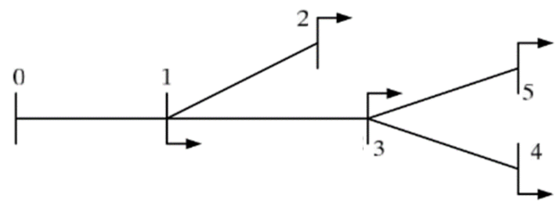

Figure 2. Test distribution network

C. *Load Shifting Strategy*

Following the selection of loads for load shifting, in accordance with the principles of DSM, a subsequent GA is deployed to formulate the optimal load shifting strategy, with the objective of maximizing the hosting capacity of the network. It is assumed that predefined percentage thresholds of the total 24-hour energy demand of the loads are intended for load shifting purposes. Within this stage, exploiting the 24-hour voltage or current profile of the node or line constraining hosting capacity within the DN, the GA aims to align the load profiles of the selected loads as closely as feasible with the voltage or current profile dictating capacity constraints. This iterative optimization process is able to ensure that the GA adapts the selected loads in a manner that prevents any capacity limitations across all hours of the day, thereby optimizing network operation while accommodating fluctuations in load demand.

In this stage, each individual chromosome of the GA consists of a number of genes equivalent to the number of flexible appliances used by the consumer. Each gene encodes the time of use of an appliance, with a predetermined load profile. The gene values are constrained by the consumer-specified time of use for each appliance.

Within the fitness function, the time of use for each appliance is mapped to its corresponding load profile. This profile is then integrated with the consumer's baseline load profile, which excludes flexible appliances. The fitness function evaluates individuals based on how closely the resultant load profile aligns with the voltage or current profile limiting the PV plant integration. Individuals that achieve the closest match are selected for further propagation in the GA process.

Finally, after obtaining the results from the GA in stage III, those results are transferred back to stage I. Within stage I, the updated load diagrams resulting from stage III are utilized, and a subsequent load flow analysis is conducted to compute node voltages and line loadings. Leveraging these data, the GA in stage I iterates to determine the new maximum PV capacity, ensuring the technical constraints of the DN are met. This recalibrated PV capacity represents the revised hosting capacity of the distribution network, thus increasing the hosting capacity of the DN while maintaining operational constrains.

III. CASE STUDY

In order to validate the model's efficacy, simulation analysis is performed on a 10 kV test DN depicted in Fig 2. For the analysis, the voltage limits of the DN nodes are set at 1.1 p.u.–0.9 p.u., while the current capacity of the lines is set to 145 A.

Fig 3 illustrates the typical generation profile of PV and load profile of loads obtained from the Macedonian distribution system operator. Additionally, Table 1 provides maximum complex power at each node, while Table 2 provides the line parameters. For this test DN, nodes 2, 3 and 5 were selected as viable locations for the integration of PV.

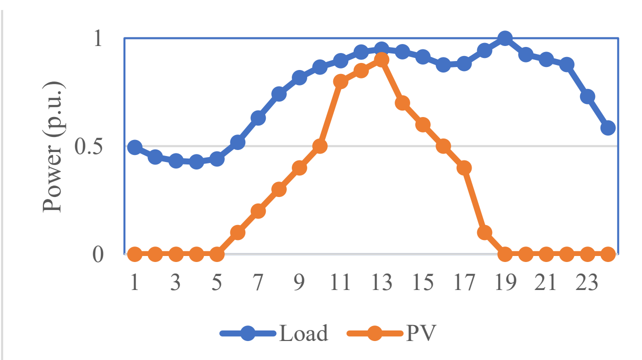

Figure 3. Load and PV profiles

TABLE I. COMPLEX POWER AT EACH NODE

Node	Complex Power [kVA]
1	400+j130
2	200+j70
3	180+j60
4	100+j30
5	140+j40

Three different scenarios were anticipated, each representing different percentages of the daily energy consumption of loads participating in demand response programs:

- Scenario I: participation with 10 % of daily load consumption.
- Scenario II: participation with 30 % of daily load consumption
- Scenario III: participation with 50 % of daily load consumption

TABLE II. LINE PARAMETERS

Line	L [km]	r [Ω /km]	x [Ω /km]
0-1	2.5	0.12	0.12
1-2	0.5	0.02	0.98
1-3	6	0.40	0.40
3-4	0.4	0.03	0.03
3-5	0.6	0.02	0.02

Utilizing the GA from Stage I, the maximum capacity of PV integration within this DN is calculated to be 3228 kW, situated at node 2, thereby reaching the current limit of line 1-2. The current profile of line 1-2 is presented on Fig 4. The value for the a^i_{jk} matrix for this DN presented in Table 3. It is obvious from Table 3 that the load at node 2 is electrically close to the line 1-2 and that the participation of the consumer at node 2 in demand response will yield maximum increase in the installed

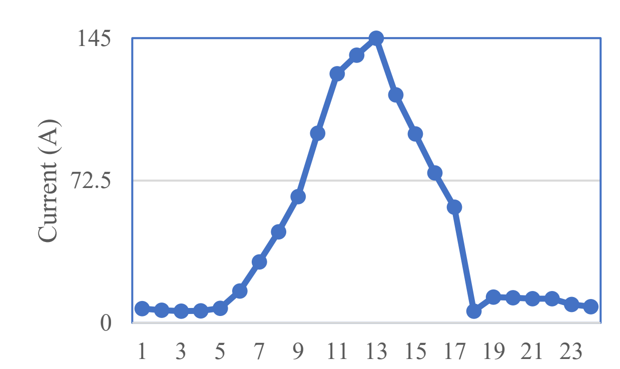

Figure 4. Current profile of line 1-2

PV capacity. For the subsequent step, the a^i_{jk} matrix data and GA and DSR principles of Stage III are leveraged to derive new load profiles aimed at maximizing the hosting capacity of the distribution network. The load profiles obtained from DSR for the three scenarios are presented on Fig 5 and the respective hosting capacities are presented in Table 4. Table 4 clearly shows how DSR can increase the hosting capacity of the DN, and those results are solely from participation of a single load, that is electrically near the node or line that constrains the first scenario, the load participates with 440 kWh into load shifting,

TABLE III. ELECTRICAL DISTANCE PARAMETERS IN P.U.

Line	Node					
	0	1	2	3	4	5
0-1	0.87	0.12	0.12	0.13	0.13	0.13
1-2	0.03	0.02	0.98	0.03	0.03	0.03
1-3	0.40	0.40	0.40	0.60	0.60	0.60
3-4	0.03	0.03	0.03	0.03	0.97	0.03
3-5	0.02	0.02	0.02	0.02	0.02	0.98

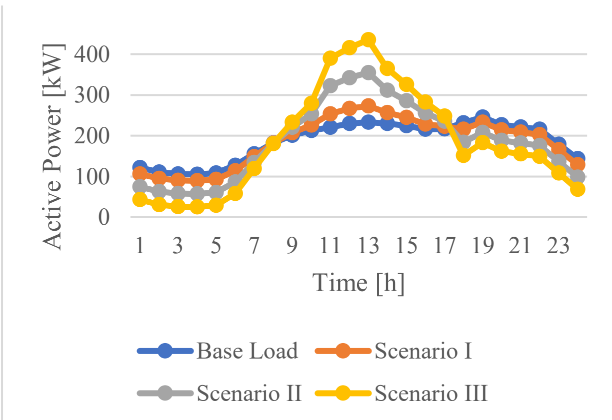

Figure 5. Load profiles for different scenarios

TABLE IV. HOSTING CAPACITY FOR DIFFERENT SCENARIOS

Scenario	Without DSM [kw]	With DSM [kW]	Incensement [%]
I	3228	3267	1.2
II	3228	3359	4.05
II	3228	3446	6.8

which yields 1.2% increase of the hosting capacity of the DN. In the second scenario, the load participates with 1320 kWh, which increases the hosting capacity of DN by 4.05 %., while in the last scenario, the load participates with 2200 kWh into load shifting, increasing the hosting capacity of the network by 6.8 %.

IV. CONCLUSION

This study aims to present a comprehensive methodology that maximizes the PV hosting capacity of a DN. The methodology incorporates a novel approach of calculating node voltages and line loadings, replacing the time consuming load flow analysis, and a novel approach for selection of loads that can participate in load shifting, thus contributing to increase of the hosting capacity of the DN. The solution utilizes GA to obtain the optimal location of the PV plant and to select the adequate loads that may shift their consumption with the aim to increase the hosting capacity of the DN. Utilizing a test model of DN for simulation purposes, the results highlighted the positive impact of integrating DSR on enhancing the network's capacity to accommodate distributed renewable energy, and also reduce the number of participants in load shifting, thus reducing the expenditures associated with DSR.

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