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PROBABILISTIC ASSESSMENT OF NETWORK HOSTING CAPACITY

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Abstract

The integration of a substantial quantity of distributed renewable energy sources (DRES) with minimum environmental impact, yet with immense uncertainty in the energy production, poses significant challenges to the distribution networks (DNs). Consequently, the evaluation and enhancement of the hosting capacity (HC) of the DNs have garnered considerable attention. This paper introduces a novel planning method for increasing the HC of a DN without necessitating expensive long-term infrastructure upgrades. A proper threshold for acceptable violations of the DN's operating voltage limits is defined and a probabilistic method for assessing the probability of occurrence of such violations is formulated, based on Monte Carlo (MC) simulations. If the probability of violations falls below the specified threshold, approval for the integration of the examined RES is granted. This framework is a relaxation of the widely applied worst-case scenario planning methodologies for addressing uncertainties in DRES integration studies. Under this approach, the maximization of the hosting capacity is formulated as a stochastic optimization problem with chance constraints. Applying this methodology to a distribution network of Greece and comparing the outcomes with the existing methodology employed by the Hellenic Electricity Distribution Network Operator (HEDNO) reveals a significant increase in HC for a certain set of candidate buses for PV installation.

1 Introduction

The ongoing energy transition from fossil fuels to renewable energy sources is critically affected by the capacity of electricity transmission and distribution networks to accommodate the unprecedented increase in decentralized renewable generation without degrading their operational security and power quality. In particular, overvoltages are the main concern for the Distribution System Operators (DSOs), especially in rural distribution lines where the renewable potential commonly exists [1–4]. In order to overcome operational challenges, DSOs tend to apply conservative limits in order to permit the connection of new renewable generation assets [5, 6]. This leads to the rejection of many renewable project applications and consequent political and social pressures to increase the hosting capacity of their networks for economic and environmental policy concerns [7].

Increasing the DNs' HC is of utmost importance for the DSOs. However, this task is complicated by the stochastic nature of DRES, resulting in intermittent energy production. DSOs face the challenge of ensuring the secure, stable and efficient operation of the DN, adhering to multiple criteria such as bus overvoltage and line overloading limits, power quality and protection concerns [8]. These factors contribute to the complexity of enhancing HC in DNs. The prevailing approach to address this challenge is to upgrade network infrastructures, however DRES control in Active Distribution Networks (ADNs) can be also effective.

Infrastructure upgrades includes the installation of battery energy storage systems (BESS) [9, 10] and capacitor banks [10], the network reinforcement via increasing the conductor size or the network expansion through the installation of new lines[11] and the installation of Flexible AC Transmission System (FACTS) devices such as dynamic voltage restorer (DVR), static VAr compensator (SVC), distributed static compensator (D-STATCOM), and unified power flow controller (UPFC)/unified power quality conditioner (UPQC) [12]. These measures are robust solutions that can securely increase the DN's HC, yet they usually require a high investment cost and usually a long-term realization.

The optimal utilization of the ADNs resources refers to the optimal operation and control of the DRES, exploiting the flexibility capabilities, including demand, where available. The control of inverters for active and reactive power setpoints of DRES [1, 2, 7, 8, 11], optimal scheduling of electric vehicles (EVs) charging [7, 8], optimal use of the on-load tap changers (OLTC) for voltage regulation [2, 11] and network reconfiguration [13] are effective ways of optimal utilization of the ADNs resources. These solutions are certainly more economic alternatives, yet in most cases the regulatory frameworks should be updated to allow the provision of such services [7]. Moreover, their implementation typically requires real time control of DERS and grid assets, enhanced network observability and thus an adequate DNs Information and Communication Technology (ICT) infrastructure.

In this paper, an alternative framework for assessing and enhancing the HC applied at the permission stage of the connection of new DRES is introduced. It is based on increasing the HC of the existing DNs in the planning phase by relaxing the operating constraints with a certain probability of violations. To this end, a stochastic methodology for assessing the voltage range caused by the installation of new PV assets in a DN is described and analyzed. This methodology can be used as an alternative to the currently applied planning methodology by DSOs based on the analysis of worst-case scenarios, namely min-max generation and load combinations [5, 6]. Similar probabilistic approaches for assessing the HC have been reported in the literature [2, 14–20] to cope with the stochastic nature of the DRES and the demand.

In the suggested methodology, the stochasticity of DRES and local demand is modelled based on annual timeseries of measurements of active and reactive power generation or consumption for estimating their joint probability distribution. Afterwards, probabilistic load flows (PLFs) are performed via MC simulations for estimating the probability distributions of bus voltages. From the voltage distributions, the cumulative probability of the occurrence of voltage violations is estimated. The approach can be applied assuming that the DSO is entitled to disconnect a certain amount of generation assets or decrease their active power output in case of local overvoltages through DRES PU-droops control, as long as the probability which roughly reflects the total annual duration of disconnection or curtailment is lower than the pre-defined bound.

The proposed methodology is applied on a model of a real Medium Voltage (MV) DN at Doliana, Ioannina, Greece. Several new asset installation scenarios are examined and assessed, using both the currently applied methodology by HEDNO and the proposed one. From this comparative study, it is observed that the HC of a certain subset of candidate buses for PV installation can be increased up to 154% if the proposed stochastic methodology is adopted.

The rest of the paper is organized as follows: Section 2 contains the mathematical formulation of the HC optimization problem under the probabilistic approach and under the currently applied approach. In Section 3 the methodology developed to address this problem is outlined. In Section 4 the results of the comparative study between the two methodologies over a real DN are presented. Finally, in Section 5 concluding remarks are drawn.

2 Problem formulation

In this work, only voltage violations are considered as thermal line limits are never violated due to robust design of the conductor sizes in the DN under examination. A violation occurs if a bus voltage deviates from its nominal value more than an acceptable limit $\alpha = 8\%$. Using a probabilistic approach the probability of voltage violations can be estimated and it should remain under a given threshold B. The optimization problem is formulated as the maximization of the total installed active power of new PV plants (P_i^{gen}) in a given subset $\mathcal{H}$ of candidate buses of the DN, under chance constraints.

$$\max \sum_{i \in \mathcal{H}} P_i^{gen} \tag{1}$$

$$s.t. P(|\frac{V_i - V^{nom}}{V^{nom}}| \geq \alpha, \forall i) \leq B \tag{2}$$

In order to proceed to a comparative study with the methodology that HEDNO is currently applying to assess the HC [5], a similar optimization problem is formulated under the worst-case scenarios constraints of HEDNO.

$$\max \sum_{i \in \mathcal{H}} P_i^{gen} \tag{3}$$

$$s.t. |\mu_v^i| = |\frac{\frac{V_i^{max} - V_i^{min}}{2} - V^{nom}}{V^{nom}}| \leq 5\%, \forall i \tag{4}$$

$$\sigma_v^i = \frac{V_i^{max} - V_i^{min}}{2V^{nom}} \leq 3\%, \forall i \tag{5}$$

Where V_i^{max} and V_i^{min} are respectively the maximum and minimum voltage values in each bus of the DN, which are evaluated under four (4) power flow studies for each combination of minimum/maximum load and generation.

Remark 1.
- *The optimization problem* (1)-(2) *is highly nonlinear since the constraints are expressed as integrals of probability distributions, whose functional form depend on the decision variables* (P_i^{gen})*. Similar chance constrained optimization problems have been considered in [17, 18]. Problem* (3)-(5) *is also nonlinear as the constraints* (4)-(5) *are piecewise linear and the operators min and max are not continuous.*
- *HEDNO does not currently perform optimization for maximizing the HC. Applications for new installations are accepted or declined based on power flows for the 4 scenarios examined. Problem* (3)-(5) *is formulated however for comparing the maximum potential of the deterministic and the probabilistic approaches.*
- *The parameter* α *of acceptable bus voltage deviation from its nominal value is set to* 8% *so as to be equal to* $|\mu_v^i| + \sigma_v^i$*, which is the maximum voltage deviation acceptable in HEDNO's approach.*

3 Methodology

In this section, the methodology developed to solve the optimization problem (1)-(2) is outlined in detail. Moreover, a note on the tool used to solve the comparative problem (3)-(5) is provided.

The challenging characteristic of the stochastic optimization problem (1)-(2) is the evaluation of the chance constraint (2). The procedure followed is the development of a probabilistic tool for the evaluation of this chance constraint, estimating the joint distribution of the input variables and performing MC simulations for the evaluation of the bus voltage probability distribution functions (PDFs) through PLFs.

Specifically, annual timeseries of measurements for the input random variables, which are the active and reactive power of the load and the active power of PV generation were taken as inputs from a distribution feeder in the region under study. The measurements are classified per hour of the day, then they are normalized to $[0, 1]$ and an empirical probability distribution function is fitted to them via kernel density estimation method with Gaussian kernels, as depicted in Figure 1.For any existing or new plant, the normalized distributions are shifted around its expected active or reactive power and their variance is properly adjusted to be about 10% of their mean. This way the marginal PDFs of the power injections and loads are obtained.

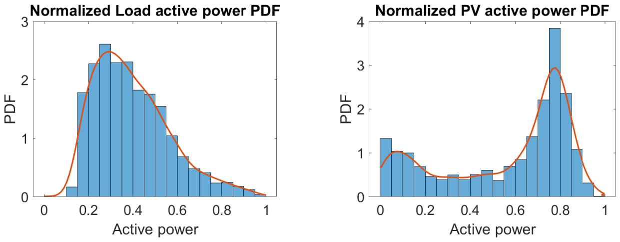

Fig. 1 Empirical marginal distributions for load and PV active power

Moreover, since in real applications these random variables are correlated [15], the correlation coefficients between the timeseries of the measurements are calculated and their joint probability distribution is approximated using the method of Copulas [19].

Sampling that joint PDF, MC simulations are performed over the linearized power flow equations for DNs (LinDistFlow) (6)-(8), [21].

$$\sum_{k:i\to k} P_k = P_i - p_i \tag{6}$$

$$\sum_{k:i\to k} Q_k = Q_i - q_i \tag{7}$$

$$v_i = v_{\pi_i} - 2r_iP_i - 2x_iQ_i \tag{8}$$

Remark 2. *MC simulation is one of the most accurate methods for PLF calculations, given that the sample size is sufficiently large. The LinDistFlow equations were used for improving the speed of the algorithm and thus applying it on samples of large size. Moreover, MC is the only approach that can handle effectively (without simplifying assumptions) studies with correlated random variables and/or nonlinear systems. Examples of the method's application on PLFs computation and HC estimation can be found in [2, 8, 12].*

Assuming an acceptable probability of limit violations $B = 5\%$, and based on the MC simulations output, the chance constraint (2) can be evaluated. In particular, the constraint (2) can be rewritten as follows:

$$P(0.92 \leq V_i \leq 1.08, \forall i) = \int_{V_{acc}} f_v(v)dv \geq 0.95 \tag{9}$$

where f_v is the joint PDF of the nodal voltages and $V_{acc} = [0.92, 1.08]^N$ is the hypercube of their acceptable values, given that the nominal voltage is 1 pu and $\alpha = 0.08$. The evaluation of the integral (9) is performed arithmetically via counting the MC PLF output samples of $V_i = \sqrt{v_i}$ lying out of $V_{acc} = [0.9, 1.1]^N$.

Finally, given the aforementioned methodology for evaluating the chance constraint, the surrogate optimization algorithm is used for solving both optimization problems (1)-(2) and (3)-(5). This optimization method is suitable for handling nonlinear, highly complex constraints of unknown functional form, which may result in nonconvex feasible sets, since it is based on approximating and not directly evaluating the constraints [22]. For this reason, it is well suited to problem (1)-(2) based on Remark 1.

4 Results

The merit of the proposed framework for the enhancement of the HC is evaluated through comparative studies over several scenarios with the existing methodology applied by HEDNO for a DN at Doliana, Ioannina, Greece.

The DN at Doliana has one substation with 2 transformers each of 25 MVA and 4 feeders. The simulation studies are carried out for feeder P290, which consists of 228 buses, 99 loads of total power 12.235 MVA and 13 PVs of installed active power 6.187 MW.

Annual measurements from existing loads and PV plants of the region have been used. The time granularity of measurements is every 15 minutes, resulting in timeseries of 35040 values for each asset's active and reactive power. These data have been classified per hour and normalized load and PV empirical distributions have been fitted to them. Proper load curve and PV production curve have been extracted from the measurements and are used for rescaling accordingly the samples for the MC simulations. For each PLF evaluation 10^5 MC samples have been used. The following scenarios have been studied.

Scenario 1: Installation of a new PV plant of 0.5 MW nominal active power at Bus 150 of the DN. No optimization was carried out in this initial scenario. Applying the proposed stochastic framework, Figure 2 shows the probability of voltage violations for each hour of daylight for this scenario.

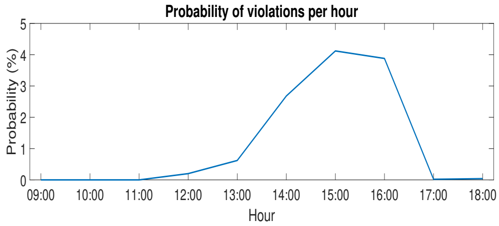

Fig. 2. Probability of violations per hour

It is observed that the probability of voltage violations reaches its maximum value at 15:00. Since the maximum probability of violations is less that the bound $B = 5\%$ this scenario of PV installation is acceptable under the proposed framework.

In Figures 3 & 4, histograms of the nodal voltages at 15:00 are presented, where the acceptable voltages limits are highlighted with red lines.

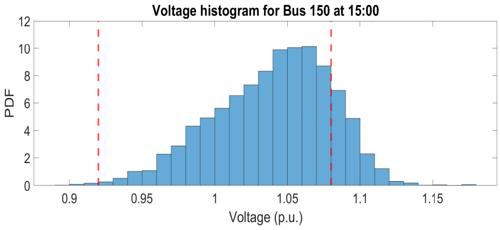

Fig. 3. Voltage histogram at bus 150 at 15:00

In Figure 3, it is observed that at bus 150, where the new PV plant is to be installed, a significant portion of the voltage distribution lies out of the acceptable limits, yet the integral of these deviations is less than the defined bound $B = 5\%$. In Figure 4, the voltage distributions at several buses are shown. It is observed that at buses near the feeder's substation and away from the PV plants the voltage distributions have a small variance and lie entirely between the acceptable limits. On the other hand, at buses near the PVs and the edge of the DN the variance of the voltage distributions increases and violations occur, however the cumulative probability of violations is within 5%. Thus this installation could be permitted. On the contrary, *Scenario 1* leads to violation of the HEDNO's methodology constraints and the installation would be rejected.

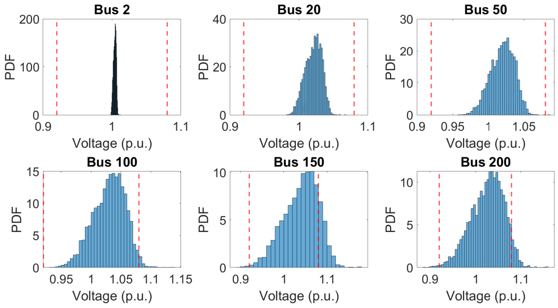

Fig. 4. Voltage histograms for several buses at 15:00

Scenario 2: Applying the HC optimization methodology for a maximum PV installation at bus 150.

For the following simulation scenarios the stochastic optimization algorithm is applied only for one hour to reduce computational complexity. The hour under examination is 15:00, as from *Scenario 1* it is observed that the probability of voltage violations is maximized there, so it stands for the worst-case hour where most violations may occur.

Table 1 Optimal HC for Bus 150

Bus	HEDNO (MW)	Proposed Optimization (MW)
150	0.370	0.533
Improvement		144%

From Table 1 an increase of 144% for the maximal HC on bus 150 is observed if the proposed framework is adopted in place of the currently applied HEDNO's methodology.

Scenario 3: Applying the HC optimization methodology for PVs installation on buses $\{17, 40, 61, 75, 110\}$.

Table 2 Optimal HC for a group of Buses $\{17, 40, 61, 75, 110\}$

Bus	HEDNO (MW)	Proposed Optimization (MW)
17	1.206	3.004
40	0.406	0
61	0.234	0
75	0.100	0
110	0	0
Sum	1.946	3.004
Improvement		154%

From Scenario 3 (Table 2), it is observed that the maximal HC is strongly dependent on the set $\mathcal{H}$ of the candidate buses and this is not necessarily increasing if more buses are taken into account. In this case an increase of 154% compared to the current methodology is noticed. The algorithms tend to concentrate the capacity to be installed at the bus nearest to the substation, which probably contributes less to voltage violations.

It should be noted that Scenarios 2 & 3 of this study provide conservative results about the maximization of HC that can be achieved through the proposed framework, since the optimization is performed only for the worst-case hour (15:00). This choice is due to limited computing resources. Given sufficient computing resources, the optimization algorithm can easily run taking into account all the hours of daylight and possibly all the buses of a DN providing significantly higher HC capabilities.

5 Conclusion

In this work, a novel DRES integration related planning method for assessing and enhancing the HC of DNs is introduced based on the acceptance of a certain probability of violations of the DNs operating limits. This framework suggests the relaxation of the existing strict regulations of the DSOs, which estimate the HC of the DNs based on the study of worst-case scenarios to consider the stochasticity arising from DRES integration. A case study using real data on a real DN at Doliana, Greece, reveals that the adoption of the proposed framework can lead to a significant enhancement of the HC for new PV plants for a defined set of candidate buses.

In the future, the presented novel DRES integration related planning framework could be further developed by considering different DRES voltage control functionalities (e.g. QU- and PU-droop control) as well novel OLTC control schemes.

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