Investigating the value of end-users controllability on improving network operational regimes

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***Abstract*—The continuous increase in the share of distributed energy resources (DER) impact everyday operation and create new challenges for distribution system operators (DSOs). In this paper, we investigate three novel concepts and their potential for DSOs. The hosting capacity (HC) concept is utilized to calculate the available network capacity for new connections during the planning phase and is the first concept investigated in this paper. We recognize the shortcomings of the HC concept and further analyze how applying the dynamic operating envelopes (DOE) concept creates the possibility to increase the network's capacity. By additional control of reactive power, it is possible to determine the total flexibility potential of the distribution network in the form of P-Q flexibility region which creates the need for the existence of local flexibility markets. Through various case studies, the impact of end-user controllability and flexibility on network conditions and change of export and import limits are analyzed. The analysis results showed that the DOE concept enable higher local production in relation to HC, while the exchange power with MV network remains similar. On the other hand the P-Q flexibility regions concept can increase this exchange power by 20%.**

***Index Terms*—distribution networks, distributed energy resources, dynamic operating envelopes, hosting capacity, P-Q flexibility regions**

I. INTRODUCTION

European regulations and directives, together with emerging global challenges contribute to the continuous increase in the share of low-carbon technologies. The trend has been significantly emphasized in distribution networks in which distributed energy resources (DER) impact everyday operation and create new challenges for distribution system operators (DSOs). Uncoordinated connection of DER to the network can cause voltage violations beyond allowable limits [1], overloading [2], voltage unbalance [3], harmonic distortion [4], and other issues related to the power quality deterioration [5]. Therefore, in order to avoid uncoordinated connections, DSOs need to consider new approaches to answering a high number of new connection requests in order to fully exploit available network's capacity and to avoid the process in which each connection request is assessed separately. A commonly used method to assess the available network capacity for new connections while respecting network constraints is hosting capacity (HC). HC is a thoroughly investigated topic, resulting in many published papers. A comprehensive review of the HC concept in terms of the historical developments, HC estimation methods, tools, enhancement techniques and future aspects is presented in [6]. Mulenga et al. [7] summarized differences in the input data, accuracy and computational time between deterministic, stochastic and time-series methods. In [8], HC assessment methods are divided into conventional and data driven (ML). However, mentioned papers neglect the application of methods in determining dynamic HC in near real-time operation, preventing the understanding of extending the HC concept to dynamic operating envelopes (DOE) and P-Q flexibility regions, that could increase the value of HC. We recognize the shortcomings of the HC concept as it is often calculated based on the worst case scenario, and further analyze how the transition from the planning to the operation phase creates the possibility to increase the network's capacity by introducing the full network's observability and controllability of DER. Such an approach is applied in the DOE concept where the import/export power of end users is adjusted continuously according to changing network conditions. If changing reactive power is observed along with the analysis of DOE, the P-Q flexibility region is calculated. The PQ

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regions should allow flexibility in the network to be used to its full potential for the purposes of providing ancillary and energy services while keeping the operation of the distribution network safe. Since control of active power has to be solved by the market, such a concept creates the need for the existence of local flexibility markets. Even though the differences between the concepts are understandable, there are no papers that investigate variations in mathematical models and describe the steps necessary to implement each of the models. To address the research gap, we propose the following contributions:

- Exact nonlinear mathematical models for calculating HC, DOE, and PQ flexibility regions with belonging various technical constraints of 3-phase LV networks are defined, as well established in the context of data requirements and usability in the planning and operation of DSOs.
- Quantitative analysis and comparison of results obtained in different concepts is presented, estimating the added value of flexible management of end users.

II. HOSTING CAPACITY

A. *The need for a more efficient assessment of new connection requests*

Accommodation of new DER connections to the network is limited by technical network constraints. Traditionally, each new connection request was assessed separately, relying on the limited functionalities of traditionally used simulation tools. As a result of uncoordinated connections requests assessment, not only long wait times for network connections and project delays threaten to slow down energy transition, but also network capacity is not optimally allocated. With the development of new tools for determining the limit at which DER can be added without negatively impacting network condition, the HC concept is utilized to calculate the available network capacity for new connections during the planning phase.

Three main groups of methods used for calculating HC of distribution network are conventional (iterative power flow based) [9], optimal power flow (OPF) based [10] and model free (ML) [11]. The choice of method to be used for the calculation depends on the available data, the required accuracy and the calculation time. If the data on the network topology and technical network parameters are known, HC can be determined using iterative power flow based or OPF based methods. The calculation times of those two methods were compared in [12], and time needed when calculating the OPF HC was 0.241 sec, while it was 2 days for iterative, scenario-based HC. Although faster, OPF methods can be unnecessarily complex for calculations in the planning phase where calculation time is not critical. On the other hand, network data is often not available, especially in LV networks, which forces DSOs to use model free HC calculation methods. Such methods are based on smart meters measurements and does not need detailed network models.

B. *Hosting capacity calculation*

Many papers present methods and calculations of HC on both medium and low voltage networks, but none presents a quantitative comparison and the contribution of novel concepts in increasing the value of HC. To overcome the issue, we present the results of the quantitative analysis in which HC, DOE and P-Q flexibility regions are calculated for the real-world LV residential feeder and import/export power of DER in each concept is compared. The feeder used for analysis is presented in Figure 1. The feeder consists of 64 nodes, 43 of which represent end users. The tool used in the analysis is pp OPF [13], the Python-based extension of pandapower. Pp OPF is the tool used for three-phase optimal power flow (OPF) calculations and can be adapted for calculations of all the above concepts. In the analysis, we use the exact non-linear and non-convex formulation of the OPF problem to ensure the accuracy of the solution.

Traditionally, HC of DER is determined based on worst case scenario. For example, to calculate the HC of distributed generation, the worst case load scenario should be observed to ensure that the network constraints are met in all possible scenarios while the generation in end users nodes is the variable to be maximized. Due to the use of three-phase OPF model it is possible to include voltage unbalance constraints (voltage unbalance factor limited to 2%) in addition to voltage magnitude (±10% of nominal) and current flow constraints (according to line parameters). Voltage unbalance factor represents the ratio of the negative and positive sequence voltage value. At each end user node, one randomly predetermined phase is available for the single-phase PV connection, while the connection power has no upper limit.

$$\begin{aligned}
\text{Maximize:} \quad & \sum_{i \in \text{buses}} \sum_{p \in \text{phases}} P_{pv,i,p} \\
\text{Subject to:} \quad & |U_{\min}|^2 \leq |U_{i,p}|^2 \leq |U_{\max}|^2 \\
& \forall i \in \text{buses}, \forall p \in \text{phases} && (1) \\
& \left(\frac{|U_{2,i}|}{|U_{1,i}|}\right)^2 \leq (0.02)^2 \, \forall i \in \text{buses} && (2) \\
& |I_{line,p}|^2 \leq |I_{\max,p}|^2 \\
& \forall \text{line} \in \text{lines}, \forall p \in \text{phases} && (3) \\
& P_{pv,i,p} \geq 0 \quad \forall i \in \text{buses}, \forall p \in \text{phases} && (4) \\
& \text{Power flow constraints} && (5)
\end{aligned}$$

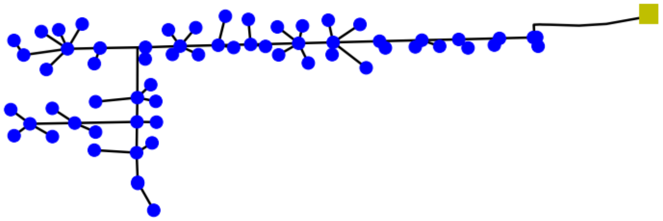

Fig. 1. Real-world LV residential feeder

Calculation results of distributed generation HC for feeder shown in Figure 1 are presented in Figure 2. Given that current flow constraints are the critical factor in this network, a case study with relaxed current flow constraints was considered to assess the impact of voltage constraints only and to compare it with the concept of P-Q regions, which provide contributions solely when voltage constraints are the critical factor. Therefore, two case studies are analyzed:

1) CS1 - voltage magnitude, voltage unbalance and current flow constraints
2) CS2 - voltage magnitude and voltage unbalance constraints

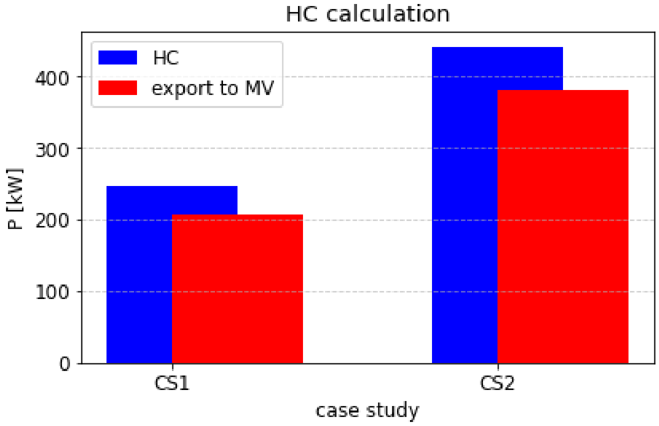

Fig. 2. HC of distributed generation calculation results

The HC value in CS2 is higher than in CS1, showing that neglecting the current flow constraint can overestimate HC. In CS2, the voltage magnitude is the critical constraint determining the HC value of 441.4 kW, while export power to MV network is 381.1 kW. Not only that the value of HC of LV feeder is available, but also the permitted export power is now calculated for all nodes/users. In contrast to calculating the connection power of each user separately, the HC concept allows for the determination of the optimal capacity distribution across all nodes, thus avoiding the time-consuming process of separately analyzing and connecting new users.

We assume HC to be a single snapshot value, conservatively calculated by defining the initial worst-case scenario, which can significantly underestimate HC. Such a conservative analysis is satisfactory for HC, which is a planning concept. On the other hand, many papers deal with time-series determination of HC, where not only the worst-case scenario is considered, but also various realistic scenarios, which results in increased values of HC. However, such a calculation still remains a planning problem since it relies on historical measurements. Therefore, we differentiate HC concept defined as a planning concept based on historical measurements or worst case scenario, from operational DOE concept which demands day-ahead or intraday electricity demand estimates and enables dynamic HC analysis in near real-time.

III. DYNAMIC OPERATING ENVELOPES

A. Operational DOE concept as a first step in flexibility evaluation

The traditional approach to investing in distribution networks is based on high expenditures for network reinforcement. However, with the development of new operational concepts, the non-essential investment for network reinforcement that is only needed at the moment of peak load can be gradually replaced by the value of flexible management of the network resources and accompanying investments in monitoring and management infrastructure. This means that the planning snapshot calculation such as HC are gradually replaced with the dynamic value of network capacity in near real-time operation. Traditionally, network access is limited by firm connection agreements, e.g. for distributed generation the 5 kW export limit for single-phase connections is commonly used in Australia [14], and the 3.68 kW limit is used in Croatia [15]. Such a conservative connection agreements together with network planning capacity assessments based on the worst-case scenario can lead to underutilization of network in some periods. Unlike static operational limits, i.e. firm connection agreements, which are predefined and unchanging, DOE adapt changing network conditions in near-real time, enabling maximal utilization of DER at all times while keeping the operation of the distribution network safe. For instance, during periods of high demand, the network's operating envelopes may shift to accommodate higher DER production since it does not consider only the worst-case scenario but near real-time measurements or their estimates. In [16] DOE is marked as an alternative connection agreement and a mechanisms for DSOs' access to flexibility. Due to the lack of local markets, such flexibility of DER to adapt to network conditions is necessary not only to maximize the potential of connected DER but also to enable the connection of new users in congested areas. Therefore, implementing DOE benefits both end users and DSO. The ability of users to adapt to the current state of the network is rewarded through increased energy exported to network in relation to the conservative case of firmed connections. Therefore, the DOE concept is the first step in evaluating flexibility which is not necessarily directly expressed in monetary units but in additionally produced kWh. On the other hand, available flexibility in the network can redirect operator investments from the network reinforcements to the availability of operational flexibility, i.e. in the availability of local flexibility markets.

DOE is often considered as a form of day-ahead or near real time HC, with capturing the changes about network status in short time intervals [17]. However, the prerequisites for implementation of this operational concept are the ability of end users to adapt to the required envelopes, their complete controllability and appropriate access to information about network status. In addition, in near real time calculations, it is important to have an acceptable calculation time. In the paper [8] the authors state that machine learning-based methods are most practical for real-time applications. However, methods based on iterative power flows [18] and optimal power flows [19] can also be applied.

B. DOE calculation

Although the DOE calculation differs from HC in terms of the time frame of determination, with minor modifications, the HC determination model based on the pp OPF tool can be adapted to DOE calculations. In addition to all the prerequisites for implementing the operational DOE concept, the model itself requires an additional time component and a constant flow of data on network consumption. DOE calculation of users' export power was performed on the same feeder (Figure 1) and the same case studies. DOE results in dynamic export power limits for each user, however the results are shown aggregated for all users.

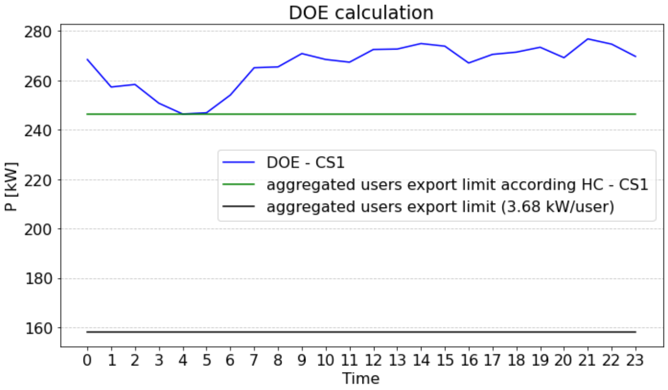

Fig. 3. Contributions of DOE and HC

The calculation was carried out based on load data with hourly resolution for one day. The results in the Figure 3 show the contribution of the HC concept to the firm connection export power (3.68kW for each of 43 users) as well as the contribution of the DOE concept to the HC determined according to the worst case scenario. It is possible to see that the value of HC is equal to the worst case scenario from the DOE and that each of the concepts introduces an additional increase in the users' exported energy into the network throughout the day.

Figure 4 presents DOE calculation with excluded current flow limitations (CS2). Although the DOE enables a higher export power of end users at some times in relation to HC, the aggregated export to the MV network remains the same. Therefore, it is necessary to develop concepts that would enable increased exchange power with MV network and control of that exchange power.

IV. P-Q FLEXIBILITY REGIONS

A. Monetary evaluation of flexibility through local markets

The flexibility of the user in the DOE concept can be marked as active power control within a reasonable interval which is rewarded with additional energy produced in relation to conservative fixed export power limits. However, for full operational flexibility that could be used to provide ancillary services to the system, an additional incentive, or financial compensation, is needed. With the previous incentive, end users can provide certain ancillary services to the operator by changing their operating P-Q point. Based on the available flexibility in the network, the system operator can determine the aggregated flexibility of the entire LV network, while respecting the network technical constraints, and thus gain insight into the operational flexibility that can be used to provide services to the MV network, without exceeding LV network limits. Such operational flexibility is represented by P-Q flexibility regions. As end users become active participants, their aggregation enables them to provide services to the network at distribution level through local flexibility markets. Such markets allow operators access flexibility of active users who are located in area of consumption. Local flexibility markets in the context of P-Q flexibility regions refer to mechanisms in which operators procure flexibility services from active users within pre-defined flexibility limits. We recognize the need for market and financial valuation of the service, however, the focus of this paper is on the method for calculating P-Q regions rather than on the market concept.

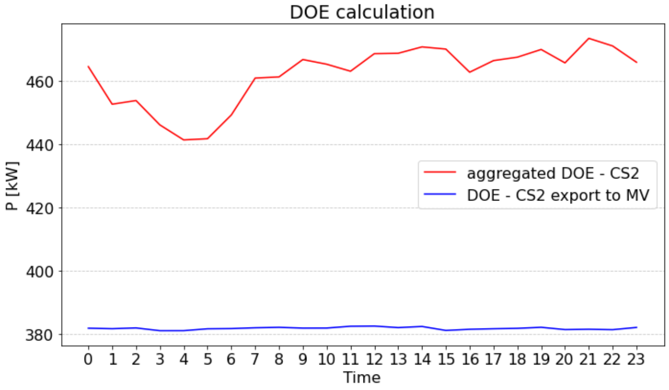

Fig. 4. DOE with relaxed current flow constraints, and export to MV

P-Q regions are traditionally determined at the TSO/DSO interconnection [20]. However, similar methods can be applied at the MV/LV level, which we investigate in this paper. Methods for determining the P-Q region can be divided into random sampling methods [21] and optimization methods [20]. The optimization based model with results is presented below.

B. P-Q flexibility region calculation

Unlike the previously analyzed concepts, the calculation of P-Q region includes an additional variable of reactive power, which is no longer connected to active power with a fixed power factor. This enables the controllability of the reactive power of end users and now it is possible to additionally influence the voltage conditions in the network, and consequently the available network capacity and the exchange power with MV network. Each user has a predifined active power and power factor flexibility interval within which it can be adjusted at the operator's request. By maximizing the active and reactive power at the MV/LV network interface in different search directions, i.e. different power factors, with defined end user variables, an aggregated P-Q flexibility region is obtained.

$$
\begin{aligned}
\text{Maximize: } & \sum_{\phi \in (0,360)} x P_{MV-LV,\phi} + y Q_{MV-LV,\phi} \\
& (0^\circ \leq \phi < 90^\circ)\ x = +, y = + \\
& (90^\circ \leq \phi < 180^\circ)\ x = -, y = + \\
& (180^\circ \leq \phi < 270^\circ)\ x = -, y = - \\
& (270^\circ \leq \phi < 360^\circ)\ x = +, y = - \\
\text{Subject to: } & Q_{MV-LV,\phi} = \tan\phi \cdot P_{MV-LV,\phi} \\
& \forall \phi \in (0,360) && (6) \\
& P_{min} \leq P_{gen,i} \leq P_{max} \quad \forall i \in \text{buses} && (7) \\
& P_{min} \leq P_{load,i} \leq P_{max} \quad \forall i \in \text{buses} && (8) \\
& -\tan\arccos 0.95 \cdot P_{gen,i} \leq Q_{gen,i} \leq \\
& \tan\arccos 0.95 \cdot P_{gen,i}\ \forall i \in \text{buses} && (9) \\
& \text{Technical network constraints} && (10) \\
& \text{Power flow constraints} && (11)
\end{aligned}
$$

In the case of unlimited end user flexibility, i.e. the user's generation and load power is not constrained, the P-Q region of all feasible MV-LV exchange operating points is obtained (Figure 5). For each point within the region, it is possible to set up users in LV network, with a certain incentive, so that the desired service can be provided to the MV network without exceeding LV network limits. However, such use of operational flexibility would require the existence of local flexibility markets. It is important to emphasize that current flow constraints are not taken into account in CS2 calculation in order to highlight the impact of reactive power control on voltage conditions. In CS1 current flow constraints are critical and reactive power control can not lead to an increase of HC and export power to MV network. Although feasible, P-Q flexibility region presented in the Figure 5 - CS2 is unrealistic because we can not count on unlimited flexibility. If realistic generation and load power flexibility intervals are observed, the P-Q flexibility region in CS2 is significantly reduced. In the P-Q region (Figure 5 - CS2) it is possible to see that with the full control of active power of load and generation, and with the control of reactive power, it is possible to achieve greater export power in MV than in HC and DOE concept (CS2). Maximum export to MV network at one of the points of the region is 465 kW which is significantly higher than that in HC and DOE, which is 381 kW (CS2).

V. CONCLUSION

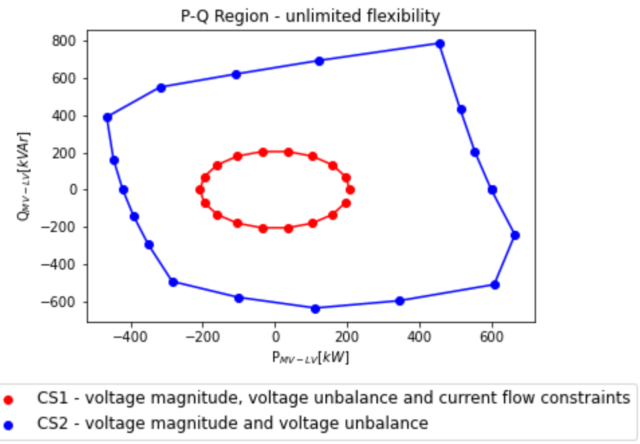

Fig. 5. P-Q flexibility region

In order to accelerate the integration of low-carbon technologies, it is necessary to move from the traditional approach to analyzing their impact on the network to innovative concepts. The innovative approach starts in the planning phase, where the hosting capacity of the network is determined with the impact of network constraints. A coordinated approach to the analysis of new connections requests reduces the duration of the procedure for separately assessing the impact of each new connection on the network, and the possibility of their acceptance into the network is determined already in the planning phase. By approaching near real-time operation, the uncertainty of data on the state of the network is reduced, and in the operational phase, it is possible to accept higher production/consumption in the network at certain times. Although participants in the DOE concept are encouraged to change their output power at the operator's request within a reasonable interval, through a higher energy delivered to the network compared to a fixed, conservative limit, more serious sources of flexibility still need to be financially encouraged. Such sources of flexibility can provide ancillary services to the system, and operators can use them to achieve the desired operating point within the P-Q flexibility region, which should include network constraints. Also, because of impact of reactive power control on voltage conditions P-Q flexibility regions concept can increase the value of HC. Although the analysis shows that the P-Q region concept provides a significant contribution to increasing HC values through enhanced export power to the MV network, it is important to emphasize that the analyzed case with unlimited flexibility is not realistic. Therefore, such an increase cannot be expected in practice. However, this paper presents a proof of concept, while future research will incorporate real-world scenarios.

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