The Role of Demand-side Flexibility in Harmonics-considered Dynamic Hosting Capacity

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Abstract

In this paper, we analyse the potential of demand-side flexibility and the importance of considering higher-order harmonics in calculating distributed energy resources (DERs) hosting capacity in low voltage (LV) distribution networks. We step aside from traditional calculations, in which hosting capacity (HC) is assessed based on the worst-case scenario and calculate dynamic export and import limits, based on near real-time electricity consumption estimates. In the scenario without modelling higher-order harmonics, the results show that upward flexibility contributes to the increase of installed distributed generators since aggregated active power increases between 0.05 and 38%, depending on the case study. When import limits are calculated, dynamic HC (DHC) also increases due to the demand-side flexibility potential, with the impact even more significant than in the case of export. Introducing higher-order harmonics in the model leads to decreased DHC in the scenario in which export limits are calculated. The decrease happens not only because of the total harmonic distortion (THD) constraint but also due to the contribution of the higher-order harmonics to the root-mean-square (RMS) voltage value. When calculating dynamic import limits, harmonic voltages increase the RMS voltage magnitude and, that way, free up additional space for the DERs installation.

1 Introduction

Hosting capacity (HC) in low voltage (LV) networks is calculated to determine the maximum allowable installed power of distributed energy resources (DERs) that does not endanger the network's safe operation [1]. However, the calculation of HC is often conservative and limits the installation only based on the worst-case scenario. Therefore, research is oriented towards finding the methods for the hosting capacity increase [2]. One of the methods for an HC improvement is implementing demand response strategies [3]. Demand response programmes and demand-side flexibility show promising results in an HC increase without additional investment in network reinforcement.

However, even after the implementation of demand response programmes or some other solution such as Volt/Var or Volt/Watt control [4], the concept of HC remains unchanged, and it assumes static export or import limits during the observed period.

A recent investigation in the field of HC assessment has focused on calculating dynamic operating envelopes or dynamic hosting capacity (DHC) in which export and import limits change over time and are calculated based on real-time network conditions [5]. Unlike traditional HC, DHC is an operational problem, so it is often based on near real-time measurements or state estimation and calculated for the following period [6]. Dynamic export and import curves can also be calculated for a whole day based on estimated or forecasted values of electricity consumption [7]. Moreover, the authors investigate the importance of voltage and current magnitude and voltage unbalance constraints in the DHC calculation. However, none of analyses consider the contribution of higher-order harmonics to dynamic import and export limits in three-phase networks. Harmonics should be considered due to their non-neglectable propagation in case of uncoordinated integration of DERs [8]. Wu and Harrison consider harmonic limitations when assessing a distribution network HC [9]. However, their work is limited to a single-phase network and static limits only.

Analysing the potential of demand response programmes and demand-side flexibility for the DHC improvement is still not properly investigated in the literature. A two-stage approach for constructing operating envelopes for each customer and demand response aggregator's participation in the electricity market is presented in [10]. However, the authors' contributions are more oriented toward market aspect and end-user privacy and not on the increase of export and import limits when end-users are flexible.

To overcome the identified gaps in the literature, the contributions of this paper are following:

- Optimization-based analysis of the impact of higher-order harmonics in calculating DHC.
- A detailed investigation of demand-side flexibility's contribution to the increase in the value of dynamic export and import limits.

The rest of the paper is organized as follows: methodology is described in Section 2, while the case studies and scenarios are defined in Section 3. The discussion on the results of the optimization-based calculated values is presented in Section 4, while the conclusions are given in Section 5.

2. Methodology

The calculation of dynamic hosting capacity in this study is based on the non-linear, non-convex three-phase optimal power flow (OPF) formulation presented in [11]. The formulation of the tool *pp OPF* is extended by harmonic constraints and harmonic source model. The harmonic source is modelled as the ideal current source, where each harmonic current is calculated from input values of the share of higher-order harmonic in the fundamental frequency current and harmonic angle. After modifying the initial formulation, three-phase OPF becomes three-phase harmonic OPF (HOPF), which is then used in the assessment of an LV network' DHC. It needs to be emphasized that the analysis in this paper is conducted from the steady-state point of view, i.e., we do not investigate harmonics from the dynamic standpoint but focus only on the quantities that can be calculated by the HOPF model in which changes happen within 15-minute intervals.

2.1. Network's Limitations

The optimisation problem is not unbounded, i.e., several technical constraints limit the value of calculated dynamic export and import limits.

The root-mean-square (RMS) voltage magnitude is calculated using (1). Relevant standards define the allowed interval of voltage values for RMS voltage and not the fundamental frequency one, which many studies neglect since they do not consider the contribution of harmonic voltages to voltage magnitude that needs to be between minimum and maximum values (2). In this study, the minimum voltage magnitude is 90%, while the maximum is 110% of the nominal voltage.

$$\left(U_{n,p,t}^{RMS}\right)^2 = \sum_{h\in\{1,\dots,H\}} \left(U_{h,n,p,t}^{re}\right)^2 + \left(U_{h,n,p,t}^{im}\right)^2 \qquad (1)$$

$$\left(U^{min}\right)^2 \leq \left(U_{n,p,t}^{RMS}\right)^2 \leq \left(U^{max}\right)^2 \qquad (2)$$

The same can be applied in the case of current constraint since the RMS value cannot exceed each line's ampacity (3)-(4).

$$\left(U_{n,p,t}^{RMS}\right)^2 = \sum_{h\in\{1,\dots,H\}} \left(I_{h,ij,p,t}^{re}\right)^2 + \left(I_{h,ij,p,t}^{im}\right)^2 \qquad (3)$$

$$\left(I_{ij,p,t}^{RMS}\right)^2 \leq \left(I_{ij}^{max}\right)^2 \qquad (4)$$

Other constraints in the optimization problem are related to voltage unbalance factor (VUF), defined as the ratio between magnitudes of negative and positive sequence voltage (5) and total harmonic distortion (THD) (6).

$$\frac{\left|\left(U_{n,t}^{RMS}\right)^{neg}\right|}{\left|\left(U_{n,t}^{RMS}\right)^{pos}\right|} \leq VUF^{max} \qquad (5)$$

$$\sum_{h\in\{2,\dots,H\}} \left[\left(U_{h,n,p,t}^{re}\right)^2 + \left(U_{h,n,p,t}^{re}\right)^2\right] \leq \left(THD^{max}\right)^2 \cdot \left(U_{n,p,t}^{fund/RMS}\right)^2 \qquad (6)$$

2.2. Demand-side Flexibility Model

Eq. (7) presents the allowed interval of change of active power $P_{load\ n,p,t}^{flex}$ of a flexible load connected to a node n, phase p and, at time period t. Active power can be either increased or decreased and maximum change can be $\pm 10\%$ or $\pm 20\%$ of the actual measured value, depending on the case study.

$$P_{load\ n,p,t}^{min} \leq P_{load\ n,p,t}^{flex} \leq P_{load\ n,p,t}^{max} \qquad (7)$$

Also, in some case studies, we assume that loads are time-shiftable, and even though the maximum allowed change of active power remains the same as in (7), additional constraint guaranteeing the equality of total daily power in the base case without flexibility and cases in which loads are deferrable is introduced by (8).

$$\sum_{p\in\{a,b,c\}} \sum_{t\in T} P_{load\ n,p,t}^{flex} = \sum_{p\in\{a,b,c\}} \sum_{t\in T} P_{load\ n,p,t}^{base}, \forall n \in N \qquad (8)$$

3 Case Studies & Scenarios

A real-world Croatian residential LV feeder is modelled in the study. The model consists of technical and topological network data, which are input needed to create a feeder's mathematical representation. Furthermore, real-world consumption measurements are used to calculate active and reactive power values. Additionally, measurements are used as demand estimates in calculating DHC in the study. Relying on real-world models enables the analysis that is not only research-oriented but can be applied in decision-making processes.

Five case studies (CS) are defined:

- CS1 – base CS in which DHC is calculated with measured active and reactive power, i.e., loads are non-flexible,
- CS2 – loads can change the value of active power for $\pm 10\%$,
- CS3 – loads can change the value of active power $\pm 10\%$ and total daily power needs to be the same as in CS1,

- CS4 – loads can change the value of active power for ±20%,
- CS5 – loads can change the value of active power ±20% and total daily power needs to be the same as in CS1.

Furthermore, two scenarios (S), defining if harmonics are observed in the DHC calculation, are considered:

- S1 – only fundamental-frequency values are considered,
- S2 – higher-order harmonics are modelled.

4 Results

Table 1 presents calculated dynamic export and import values aggregated on an LV feeder level. As can be seen from the summarized optimization results, flexibility helps increase the integration of DERs, no matter the case study. As expected, larger export and import values are achieved in case studies in which loads are only flexible and not necessarily time shiftable. In the case of calculating export limits, harmonics decrease aggregated power in comparison to S1, both due to the contribution of harmonic voltages to the increase of RMS voltage magnitude and due to reaching the THD threshold value. In the case of calculating export limits, the consideration of harmonics has the opposite effect. As mentioned before, harmonic voltages contribute to the increase of voltage magnitude, allowing penetration of additional consumption units before reaching the minimum voltage magnitude. However, this is a specific case since THD threshold values are not met before other technical constraints.

Table 1 Aggregated export and import values

	Export (kW)		**Import (kW)**	
	S1	**S2**	**S1**	**S2**
CS1	12059.79	11592.56	3713.64	3824.82
CS2	12266.39	11904.52	4428.87	4540.00
CS3	12066.78	11792.23	3880.85	3995.54
CS4	12472.99	11839.65	5126.68	5243.29
CS5	12075.93	11774.05	4028.11	4147.45

Figure 1 shows calculated export limits in each period of the day. Dashed curves represent the S1 results, and the benefit of flexibility is seen from the shift of the curve up the y-axis. Curves representing the results in S2 are lower on the y-axis, which is in line with the summarized results in Table 1. Harmonics increase the RMS voltage magnitude, which leads to quicker reaching the upper bound voltage bound. Additionally, THD threshold values are reached in several time periods, which is an additional factor limiting the installed DERs power. The difference between upward/downward flexibility only and demand time-shifting can best be seen by the curves' intertwining, meaning that in some case studies, the increase in active power needs to be compensated. Compensation happens in time periods in which the impact on the objective function value will be the lowest.

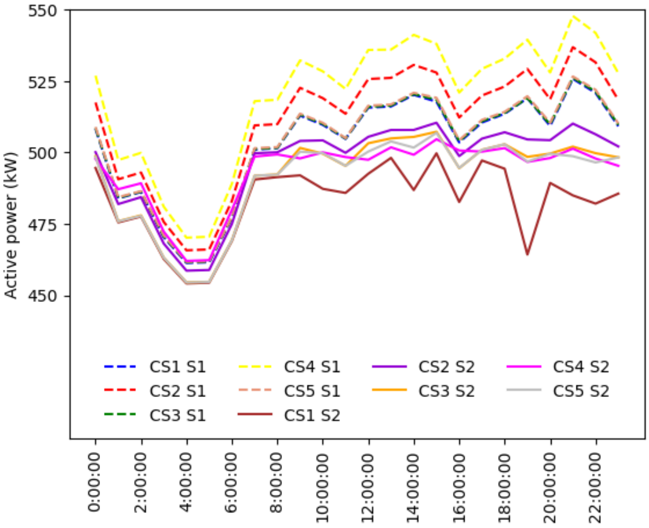

Figure 1 Dynamic hosting capacity – export

Figure 2 presents the calculated dynamic hosting capacity in the case of import limits. The conclusions remain the same as the one drawn by analysing the results presented in Table 1 and are in line with conclusions based on the export limits calculation. When compared to the base case study (CS1), DHC improves when demand-side flexibility is implemented in the optimisation model. Furthermore, the expected benefit of modelling flexibility with the increase/decrease of electricity demand only is also seen in the graph. However, time-shifting disturbs end-users' comfort less and is a favourable approach in many studies. What is interesting in the case of calculating dynamic import limits is that harmonics do not reduce the interval of active power values but free up additional space instead. Since harmonic voltages contribute to the increase of RMS voltage magnitude, it creates a scenario in which consumption units of greater power can be installed in a network. However, such a conclusion is not unambiguous and is valid only in the case in which voltage constraint is the one reached first. When calculating dynamic import limits in this study, VUF, THD, and current magnitude values change over time and in some periods, they come relatively close to threshold values. However, none of these constraints is reached before voltage magnitude, and therefore, it may seem that harmonics positively impact calculating network limits. This phenomenon requires further investigation in order to determine what happens in other cases and how much flexibility potential helps to avoid reducing the installation capacity of DERs.

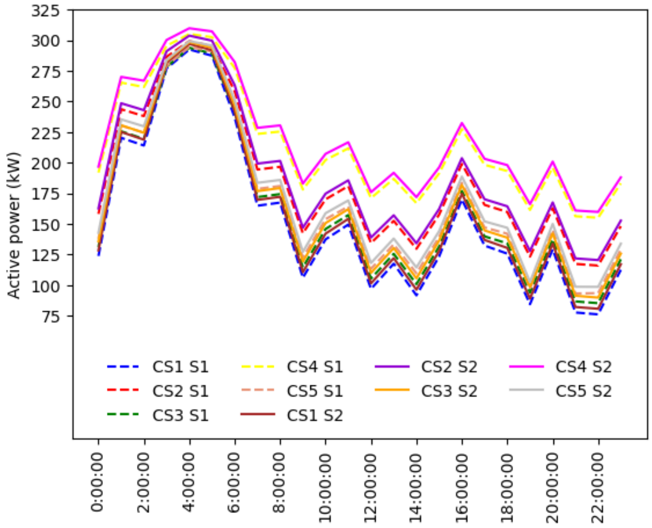

Figure 2 Dynamic hosting capacity – import

5 Conclusion

Three-phase harmonic optimal power flow has been applied in analysing demand-side flexibility's potential in calculating dynamic export and import limits. Loads are modelled in two ways: the first one, in which loads only increase or decrease their power consumption and the second one, in which loads are time-shiftable, and compensation is needed for every demand increase or decrease.

The results show the improvement of DHC in the range from only a few kW to over 1400 kW on a feeder level. Furthermore, the importance of modelling harmonic constraints is presented since it affects the value of the objective function both when calculating export and import limits. However, some of the results are not unambiguous, and further research in the field of harmonics' contribution to DHC is necessary.

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