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Distribution network hosting capacity calculation enhancement through time series analysis and performance index

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Abstract. The increasingly ambitious renewable energy targets highlight the system integration of intermittent generation as an important research area. Achieving these targets poses a significant challenge for distribution system operators and transmission system operators all around the world. The human resource shortage and time constraints faced by network operators further exacerbate these issues, and as a result, conventional network development solutions do not always provide the optimal solution.
The solution to the problem is not solely to be found in new tools. Calculation methods for hosting capacity usually relies on worst case scenario assumptions and artificial system states in practice. In this paper different hosting capacity calculation methods were evaluated to provide specific insight to the characteristic differences. The role of serial voltage regulators and conventional network development tools were also assessed. The paper covers the additional capacity that can be unlocked through network development tools. The methods are compared through time series deterministic load flow simulations for both the base network and certain network development scenarios.

Key words. Hosting Capacity, Network development, renewable generation, Voltage fluctuations, Serial voltage regulator

1. Introduction

Due to carbon neutrality efforts, the number of solar power producers is steadily increasing across the world. In Hungary, an overview of the transmission system operator's statistics shows that between 2022 and 2023, the number of solar power producers grew by more than 36% compared to 2022. Additionally, between 2023 and November 1, 2024, the installed capacity increased by another 1312.5 MW, surpassing 7.3 GW [1], which is roughly around the system peak load. Within the framework of the RepowerEU strategy, which primarily aims for independence from Russian energy sources, the European Union plans to install a total of 420 GW of photovoltaic capacity by 2030, in addition to existing capacities [2]. This goal is also reflected in the Hungarian National Energy and Climate Plan, where it is expected that by 2030, photovoltaic capacity in Hungary will exceed 12,000 MW, and wind power producers will reach 1,000 MW, while the peak system load is around 7,500 MW [3].
To meet these connection demands while also ensuring compliance with voltage, frequency, and other electricity supply regulations, network development tools are required. In addition to specific tools, another possible approach is the precise definition of so-called renewable hosting capacity, as the currently accepted and practically applied methodology often involves significant simplifications and rule-of-thumb estimations.
Hosting capacity (HC) refers to a quantified characteristic of a given line or substation area that clearly determines the total capacity of renewable energy sources that can be installed at the connection point without violating any quality standards of the electricity supplied through the line. Our work covers the key points of HC related research and identify the research gap covered by this paper.
The paper is organized as follows. Chapter 1 covers the introduction, while chapter 2 introduces the review of current HC calculation practice, as well as the proposed novel approaches in the calculation process and modelling technique. Simulation scenarios and result evaluation is covered by Chapter 3, while Chapter 4 summarizes the conclusions. The main contribution of the paper is the in-depth analysis of time series load flow calculations for the combined simulation of medium and low voltage (LV) networks.

2. Methodology

This chapter introduces the HC definition, and the evolution of the calculation methods until the current state of the art. The proposed novel index approach, and the modelling framework provides a basis for the simulation studies which shows the key contributions of the paper.
The need for a precise definition of HC is increasing with the deployment of renewables, and in the future these definitions could form a backbone of network development principles to be taken into account for all connection needs. In this context, a large number of studies on the subject have been carried out, starting from the early 2000's. [4] presents a detailed and comprehensive research on the history, importance, definition methods and influencing factors of HC.

The authors have processed about 1757 articles on HC, distributed generation, renewables, solar panels, electric car chargers, HC definition, HC enhancement techniques and machine learning.

According to the authors of [5] two different approaches to HC definition can be found. In the first one, the quality of the energy supplied to the electricity grid can be characterised by a so-called "performance index (PI)" variable, which shows the degree of compliance with the current quality requirements. In addition to the PI approach, it is also popular to define different ratios. The most common ratios are:

- Generation capacity - transformer rated power
- Generation capacity - peak load.
- Generating capacity - available surface area to install solar generators

By defining these ratios, it is possible to quantify the effects of the generation integration, considering the framework of power quality requirements. The authors of [5] achieved a HC value of 97.3% compared to the maximum consumption experienced on the LV grid by using different energy management solutions. [6] discusses in detail the options for defining HC. The quantity, type and reliability of the available data strongly influence the analysis, and several methods are widely used to take these factors into account. One of the most common solutions that gives a "near accurate" result is the so-called "worst-case hour approach", where only the extreme operating conditions critical for the infrastructure are analysed, rather than a complete time-series data set. [7] proposes three different methods to assume the distribution of Photovoltaic (PV) along the feeders based on the solar roof potential, and subsequently to estimate the PV hosting capacity of these feeders. [8] presents a streamlined method for assessing the PV hosting capacity of distribution networks. In case of rural, long overhead line network the usual limitation is the voltage magnitude change. There are a set of rules for that (5% voltage drop on the medium voltage (MV) line, as well as the limitation of 2% between voltage magnitudes in case the generator is running on 100% and being switched off. Based on the literature review, this paper proposes enhancement of the calculation to have a better view on HC.

A. The definition of HC

The HC can be derived from a set of parameters that characterize the quality of the electricity supplied by the network, such as line loading, transformer loading, voltage magnitude, and stability. The HC value for a given line will be determined by the most stringent condition among these parameters.

To generate criteria from methodologies, certain threshold values must be established. In this paper, thresholds are based on the values given in the EN5160 standard, the grid code, as well as on the nominal loading of series elements for current loading. In our work we compute HC using a time-series deterministic approach for a given network. From the available consumer and generation profiles and measurements time series data were created to perform symmetric AC power flow calculations, from which specific operating states of the network can be evaluated.

In our modelling study, we compare the HC values calculated with different approaches and observe the capacity increase on the line using innovative and conventional network development tools. The analysed network is a substation area, which consist of overhead lines, representing a rural area. The reviewed HC calculation methods were compared for a base case. Then different network development methods, such as a serial voltage regulator, increased cross section lines were examined.

B. Modelling

The main objective of the modelling work is to compare the HC determined by the currently used “2% rule” with the HC derived from the newly developed methodology, as well as to examine the impact of a serial voltage regulator and other conventional tools on this variable. The analysis was conducted in a deterministic manner using a positive-sequence power flow simulation on the medium/low voltage network that I have selected.

The modelling follows a step-by-step approach: first the base case scenario is being assessed, then the HC values are determined by both the 2% rule and the proposed methodology. It is important to note that in this study, a fixed location is assumed for the generators, meaning only the power, not the placement of those are variable.

Once the HC of the line is determined, the impact of the network development solutions can be calculated.

3. Simulation studies

A. Test network

The chosen network is a substation area with longer line sections. The data for the network was downloaded from simbench [9] which has a database for similar and other high/medium and LV network variants. Simbench can be easily integrated into the pandapower [10] environment.

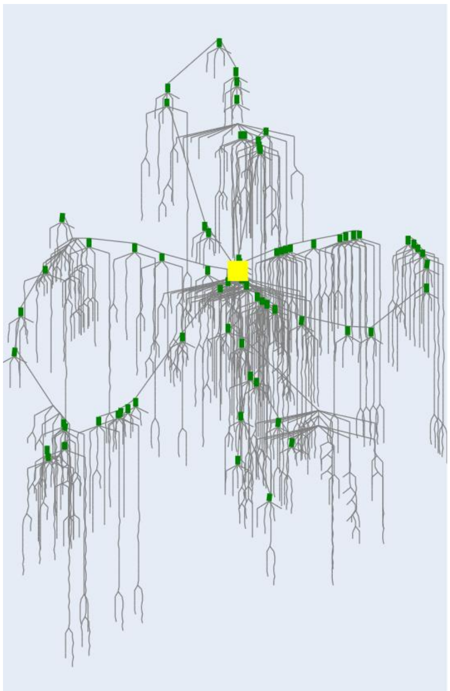

Fig. 1. The topology of the model used in the simulations

The figure above shows the topology of the test network. In the Simbench database, there are several different network designs available depending on whether the user is looking for a rural or urban network. The model we have chosen is a rural network that has the required line lengths. In green are the locations of the medium/low voltage transformers. In the middle, marked in yellow, is the external grid and the high/medium voltage transformer connected to it.

The consumption and generation profiles of the 20/0.4 kV model are mapped using synthetic consumption and generation profiles. Each consumer and producer have a nominal power value, which is multiplied by the profile value representing the time instant to obtain the consumption and production values for that time instant. In numerical terms, the supply area has 26.56 MVA of renewable energy resources, which exceeds the 25MVA rated power of the substation transformer. The transformer is equipped with On-load tap changer (OLTC) control. The previously mentioned 26.56 MVA power includes all low-voltage household-sized small power plants, 6 medium-voltage wind farms (each about 2 MVA), 3 biomass power plants (2 MVA), 3 biomass power plants (2 MVA), and 3 wind farms (2 MVA). The total length of the network is 214.33 km.The total installed power of the network load is 18 MVA, of which 5 are MV industrial consumers. The simulations were applied to the whole substation area, however, one of the main elements in determining the HC value, the voltage problem, is a local phenomenon, so it was necessary to examine locations individually. Thus, the feeder below was selected and will be further investigated for the analysis.

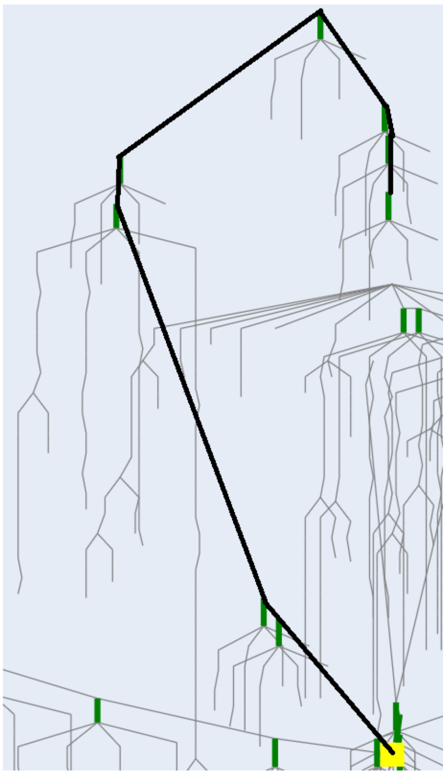

Fig. 2. Selected MV line with the LV network attached

The line includes a total of 1.29 MVA of low-voltage solar generation, as well as an additional 790 kVA of medium-voltage generation units, consisting of a 125 kVA solar farm, a 385 kVA hydroelectric plant, and a 280 kVA biomass power plant.

B. Base case

For time series analyses, predefined profiles were used. Simbench also provides consumption and generation profiles for the networks, which multiplied by the nominal power, give a time-varying behaviour. The profiles were available at 15-minute resolution for a full year, so the run time was chosen to be a full year.

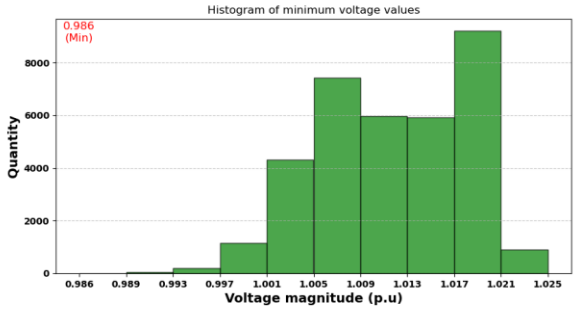

Fig. 3. 1-year long time series results – minimum voltage

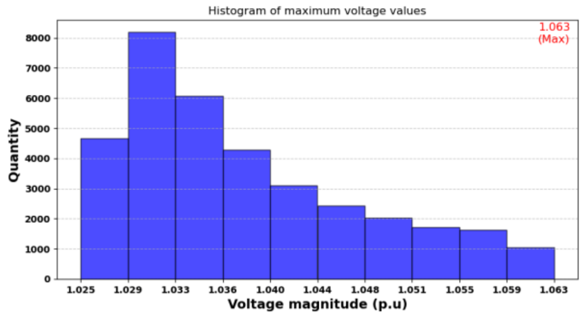

Fig. 4. 1-year long time series results - maximum voltage

The histograms in the two figures above show the minimum and maximum voltage distributions for all time points of the one-year run. Given the large size of the data set of annual run results, the maximum/minimum voltage values and maximum transformer and line loadings were recorded at each time point. This approach can give a good picture of the times when limit violations occur. The figures above clearly show that the maximum voltage values for the whole network do not exceed 1.063 v.e, an increase of 6.2%. This does not violate the limits set out in either the Guaranteed Services (7.5% for LV as the local service regulation in Hungary) or the MSZEN50160 standard. It should be mentioned that due to the methodology of the simulation studies, where the timestep is 15-minutes long, therefore rapid voltage changes are not considered by the studies.

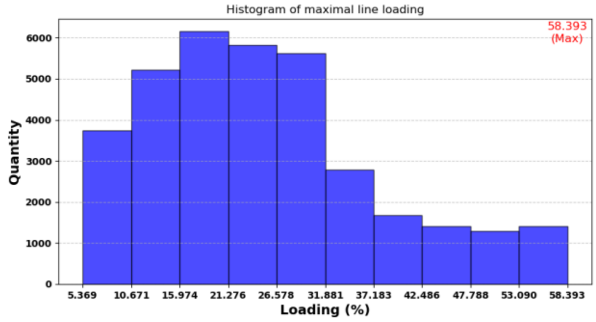

Fig. 5. 1-year long time series results – Line loading

The figure above shows the loading of all lines in the entire station area. The maximum load does not exceed 60%, and none of the transformer loads exceed 42%, so loading conditions do not constrain further generator connections. The increase in generator output is varied by the *scaling attribute* of the installed static generator elements, which is used to give a multiplier for both active and reactive power generation. For the generator profiles or generators, no reactive power production is defined, so the apparent power that will give the HC is equal to the active power of the generating unit. Hence, the impact analysis was done by varying the power output of static generators connected to the MV and then the values of the overall network were examined.

C. 2% rule

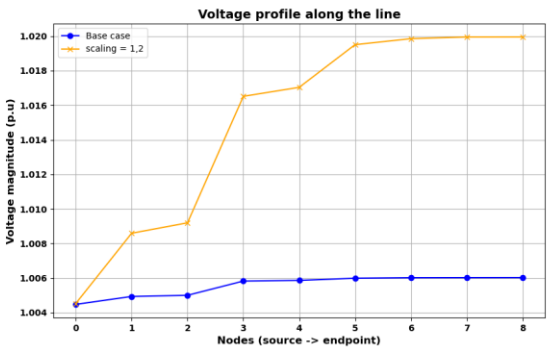

Fig. 6. Voltage profile along the line in the base case (blue) and at the HC point with the 2% rule (yellow)

The figure above depicts the results for the HC. This method considers an unloaded network (loads and LV generation) and then turning all MV generation at the same time on. HC is achieved when any node of the MV network encounters a voltage rise of 2% (1,02 per unit). This was achieved with a total amount of 948 kVA generation on the MV network.

D. New HC methodology

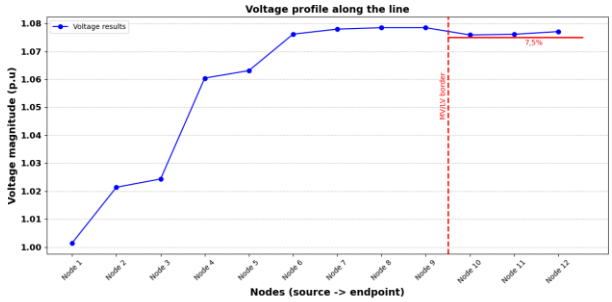

Fig. 7. Extreme operation state- Voltage profile along the line (MV-LV)

The figure above depicts the voltage profile of the MV and LV network (border marked with red dotted line) and the limit regarding the voltage value for the LV system. This was achieved at a generation value of 5.530 MVA, which is compared to the previous 2% methodology is more than 5,5 times increase. The magnitude of the current load does not exceed 60%, therefore if the voltage problem is solved a great amount of capacity can be achieved. For this purpose, an In-line Voltage Regulator (IVR) device is incorporated in the model, with the parameter settings of a real life device

E. Voltage regulated case - IVR

Pandapower does not include an IVR device as a network element, but a series OLTC transformer with sufficiently low losses can provide a suitable replacement. We have therefore used this approach in our modelling.

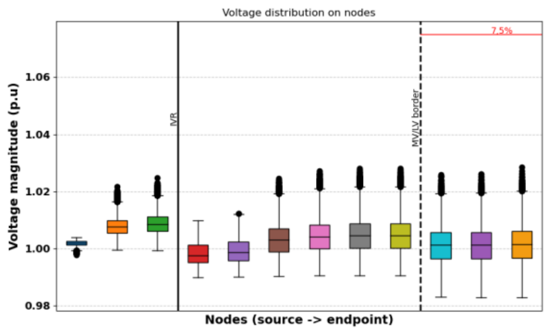

Fig. 7. Box-plot figure of node voltage values along the line

The figure above shows the results obtained with the device already installed using the previous *scaling* (*scaling = 7*). The secondary side of the device was marked with a black line, after which the voltage value stays around the nominal value of 1. This shows that the device can effectively regulate the voltage on the line, so that the voltage value at the node never exceeds the limits of the device's controller, therefore the voltage here stays between 0.99 and 1.01 relative units.

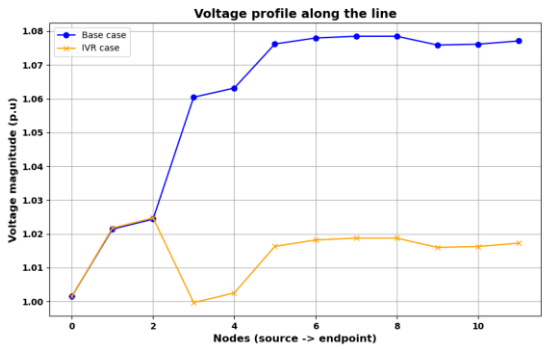

Fig. 8. Voltage profile along the line in the base case (blue) and with the IVR device installed (yellow)

The effect can also be seen in the extreme operation state's voltage profile, with the orange line showing the voltage profile at the same point in time of the already developed network, which includes the regulator. Thanks to the device, the voltage at the end of the line does not exceed 1.02 relative units, which means HC is increased.

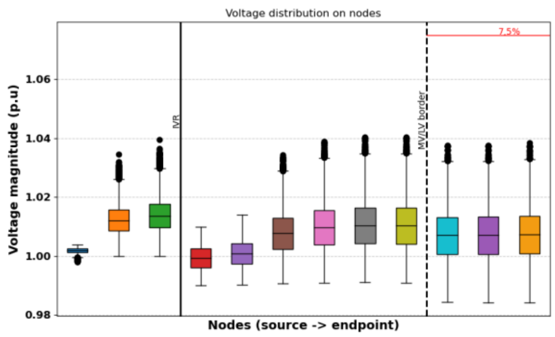

Fig. 9. Box-plot figure of node voltage values along the line

A limit violation occurred at *scaling* = *12*. The figure above shows that the IVR still effectively handles the voltage elevation effect caused by high renewable penetration. Nevertheless, the current load of the line is already at the limit, the figure below shows the distribution of the current load values of the line sections expressed as a percentage from the beginning of the line to the end point of the MV network. Already at the beginning of the line, in extreme operating conditions, the 100% load is reached, which is the real HC value according to the framework.

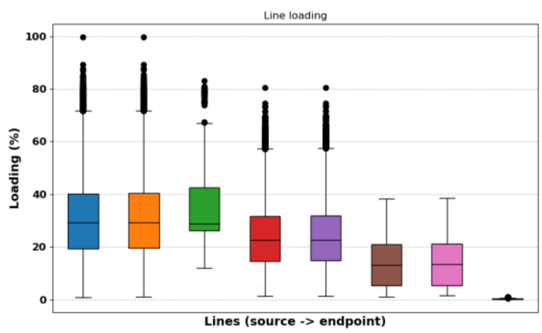

Fig. 10. Box-plot figure of line current loading along the network

The HC value with the IVR device was thus 12*790 kVA = 9.48 MVA. It should be noted that this HC is indicative in this generation location and with the use of this network development device. The current value can be further increased by further network developments (cross sectional increase, building new lines etc..). The IVR device was effective in addressing the voltage problems encountered in the early stages of the study, however, due to the operation and design of the device, it does not address the current load problems.

F. Cross section increase

To get a full picture of the potential of the IVR, conventional alternatives have to be evaluated. From our previous simulations of the impact analysis, it could be seen that the limiting factor for HC was first of all the exceeding of voltage limits in all cases. To further increase the HC value, it is necessary to increase the cross section of the whole MV line. After examining the cross-sections of the other lines coming from the substation transformer in the supply area, an aluminium line with a cross-section of 120 mm^2 was a reasonable choice and the entire 15.2 km long MV line was replaced.

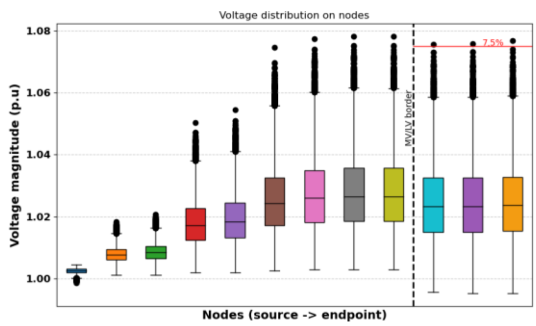

Fig. 11. Box-plot figure of node voltage values along the line

The figure above shows the results after the cross-section expansion, already after finding the HC, which resulted in a *scaling* value of 19, giving an installed power of 19*790 kVA = 15 MVA. In the present case, a voltage limit has been violated, which is clearly visible in the extreme values of the LV nodes marked by the dashed line.

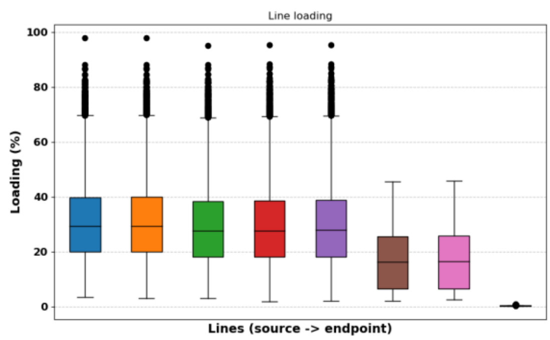

Fig. 12. Box-plot figure of line current loading along the network

The figure above shows that although the current load value is close to the limit, it is still a few % below the 100% load.

4. Conclusion

In the literature review, the paper presented a central theme of the changes occurring in the currently dynamic energy sector, the penetration of solar PV generation units in Hungary, supported by data publications from the Hungarian transmission system operator. An analysis was conducted using international literature on the currently actively researched topic of HC. Explicit attention was paid to the rules of thumb currently used in practice, as well as to the limiting effect of which was later supported by simulation results in the modelling phase of the work. The main objective of the modelling work was to investigate the impact of the currently used 2% rule and novel methods for HC, while comparing IVR and conventional cross section increase. This was investigated deterministically by means of a positive sequence power flow simulations in the supply area of a complex high/medium voltage station of our choice. The modelling used time sweep method, initially running the base case (*scaling=1*) and then examining the HC made available by the 2% rule. It is important to note that in this work, the location of the generator as given, so the location was not changed, only the amount of power delivered to the grid. After examining the supply area, the HC value of a particular line was considered, since the voltage problem that occurs is local, i.e. it has no spill-over to other lines, and thus needs to be examined separately. After determining the HC of the line, the impact of network development solutions were assessed. While the rule of thumb used by distribution licensees gave a HC of 950 kVA, our methodology gave a HC of more than six times considering only the MV line and four times considering both MV and LV limitation, this is 5,925 MVA and 3,950 MVA in power dimension respectively. With network development tools, the HC value was even higher, 9.5 MVA for IVR and 15 MVA for cross-section extension.. The additional capacity achieved by the deterministic methodology would significantly facilitate the efficient system integration of distributed generators, bringing them closer to the limits of grid infrastructure utilisation. This fact will become more and more relevant and decisive in the coming period, due to the increasing openness of distribution licensees and the growing deployment of innovative devices (at MV and LV), whose presence will guarantee an ever-increasing adaptive capacity and controllability of the network, which will certainly not be an appropriate starting point for rules of thumb. The subject holds further potential. Of the HC definition methods that were analysed in the first chapter, this paper only dealt with the deterministic approach at the modelling level. Other possibilities are, for example, the introduction of stochastic profiles and methodologies on the network and the addition of a modelling study by changing the connection point of the generating units.

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