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The impact of different PV system grid integration approaches on voltage profile, grid losses and behaviour of PV system owners

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Abstract. Distribution grids in individual countries inside the European Union have different properties, while the grid operators use different approaches to integrate photovoltaic (PV) systems into the grid, which influences the voltage profile, grid losses and grid's hosting capability. This work deals with a 0.4 kV distribution gird characteristic for the Slovenian countryside. The grid users are relatively sparsely distributed in the space. The distances between them are relatively long, while the load distribution among individual phases is unbalanced. Three different approaches to the integration of PV into the grid are discussed. The one used before 2012 with the concentrated larger PV units placed close to the transformer busbars, the one introduced with a net-metering scheme where larger PV units are randomly distributed in the grid, and the one where smaller PV units are evenly distributed throughout the grid. The case study discusses the impacts of the three approaches on the proper voltage profile provision, network losses and behaviour of the PV system owners.

Key words. Low voltage distribution grids, approaches to integration of PV systems, voltage profiles, grid losses, behaviour of the grid users.

1. Introduction

Political decisions inside the European Union (EU) resulted in the European Green Deal [1], the implementation of which should provide a climate-neutral and fossil carbon-free energy supply for Europe by 2050. The resulting Green transition leads to extensively utilising locally available renewable energy sources, where photovoltaic (PV) systems play an essential role. In all EU countries, PV systems are recognized as technology suitable to transform solar irradiance into electricity without direct emissions or environmental impacts. When installed on the roof surfaces of houses or similar buildings, most PV systems are connected to distribution grids. The density of the population and grid users influences the distribution grid properties and topology. Combined with the grid operator approach to integrating PV systems into the grid and different national policies that stimulate investments into PV systems, all together influence the voltage profile, grid losses and behaviour of PV systems' owners.

Many research papers dela with the integration of PV systems into electric grids. The authors in [2] and [3] use different approaches to address the penetration and placement of renewable energy sources (RES) based distributed generation (DG) units in the grids. The security-constrained optimal placement of RES-based DG units is discussed in [4], while the authors in [5] use battery storage to minimise losses in electric grids with high penetration of DG units. The challenges, problems, and solutions related to transmission grids required to foster large-scale penetration of RES are discussed by the authors in [6]. Some of the techno-economic aspects of the PV systems based on yearly net self-sufficient electricity supply are treated in [7] and [8]. The usage of active elements to improve grid operation is discussed in [9], while [10] presents the steps required to obtain models suitable for optimizing distribution grid operation.

The primary objective of this work is to showcase how deliberate strategies in integrating PV systems can effectively reduce grid losses and bolster the capability for accommodating more PV systems onto the grid. Distinguishing itself from similar works, this research takes into account grid users' aspirations for enhancing self-sufficiency in energy supply, along with considerations of grid losses and hosting capacity. The paper meticulously examines the ramifications of grid operator approaches to PV system integration on voltage profiles, grid losses, and the behaviours of PV system owners.

2. Analysis

The analysis is performed as a case study. A 0.4 kV low-voltage distribution grid with phase-unbalanced load distribution, well-known grid configuration and parameters, measured load and voltage time-dependent profiles and taken steps for model preparation described in [10] was used as a test object. The measured time-dependent load profiles and normalised daily PV power generation profiles for characteristic days in individual months were used together with the grid model to evaluate the impact of PV systems on voltage profile and grid losses for different approaches that were used for the grid integration of PV systems in Slovenia in the past years. The analysis was performed for steady-state operation in 15-minute time steps over the entire year using a three-phase Backward Forward Sweep (BFS) load flow calculation method [9] and [11] to [13]. Kron reduction [14] was used to transform the 3-phase 4-wire system into the 3-phase 3-wire system, considering the parameters of the neutral conductor. The constant power model was used for all loads since the load type was unknown while the measured load profile was available.

In this work, three different approaches to the integration of PV into the grid were discussed.

In "**approach I**", larger PV systems were grouped and connected to a dedicated line close to the transformer bus bars. This approach was abandoned after 2012.

In "**approach II**", PV systems with a power of 11 kWp and more were randomly placed in the grid based on the investors' interests. This approach was introduced with the net-metering scheme. It often resulted in the concentration of PV systems on individual feeders and the loads on the other feeders, making it challenging to provide proper voltage profiles in all feeders. This approach will be abandoned together with the net-metering scheme.

In "**approach III**", smaller PV systems and loads should be distributed evenly along the feeders, enabling better flexibility regarding the provision of proper voltage profiles and higher hosting capability, especially when combined with smaller local storage units and energy flexibility services.

3. Grid and test conditions

Graphical Information System (GIS) presentation of the discussed test grid is presented in Fig. 1. The grid contains the transformer Dy5n 20 kV / 0.4 kV and the feeders. Only those feeders with the users marked in red were considered in the analysis.

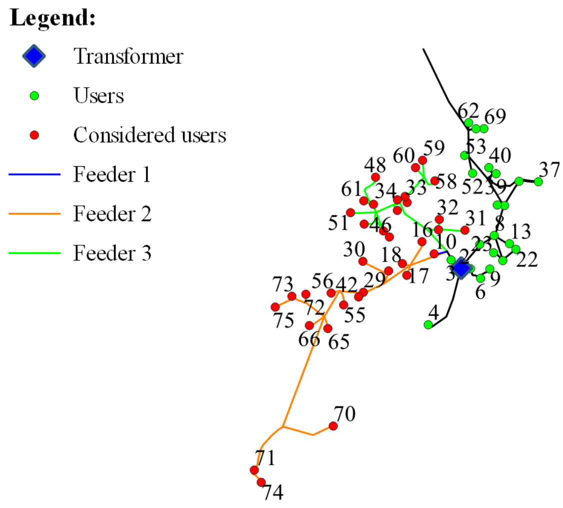

Fig.1. GIS presentation of the discussed grid

Fig 2. shows the tree diagram of the test grid corresponding to Fig. 1, which was used in BFS-based load flow calculations. Our observation was focused on Feeders 1, 2 and 3, marked in blue, red and green, respectively. Other grid users were considered, while the results are not included in this work.

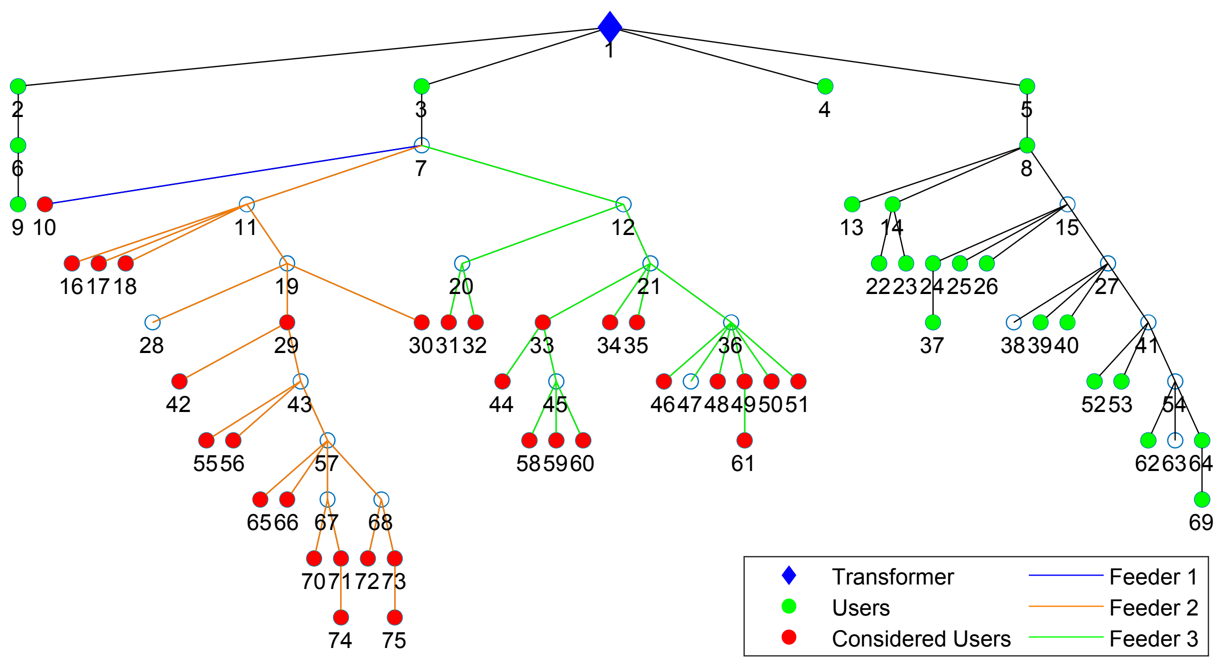

Fig. 2. Tree diagram of the discussed low-voltage grid

Figs. 3 and 4 show the time-dependent load profile measured on the transformer terminals in June and December. The first represents the lowest and the second the higher monthly load. The corresponding time-dependent voltage profiles are shown in Figs. 5 and 6 as root mean square (RMS) values for the three phases (L1, L2, L3).

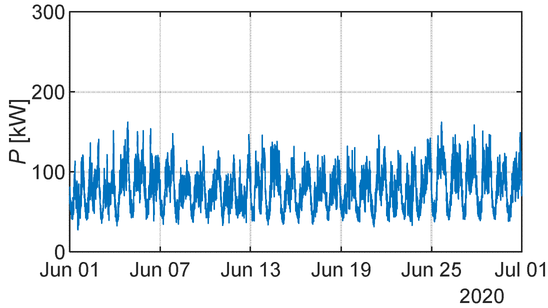

Fig.3. Transformer load profile for June

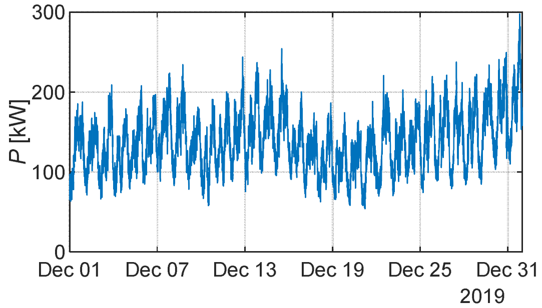

Fig.4. Transformer load profile for December

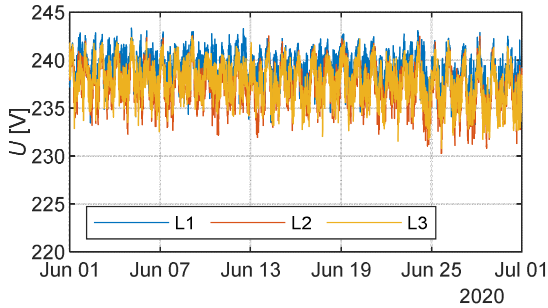

Fig.5. Transformer voltage profile for June

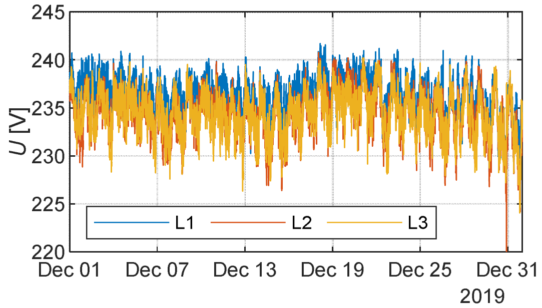

Fig.6. Transformer voltage profile for December

Fig. 7 shows the normalised time-dependent output active power profiles of a unity PV system for a characteristic day in each month. Multiplying the active power profile with the peak power of the PV system in kWp gives the daily time-dependent output active power profile of a PV system for a characteristic day in each month.

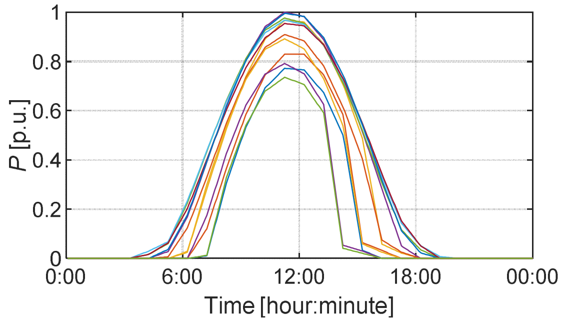

Fig.7. Normalised time-dependent output active power profile of a unity PV system for characteristic day in each month

The analysis was performed in 15-minute intervals over the entire year, where actual load profiles and PVgeneration profiles (see Fig. 7) were considered phase or three-phase load. The obtained results are presented in the next section.

4. Results

Although the analysis was performed over the entire year, in this work, only the results obtained for June 12 in the time interval between 12:30 and 12:45, where the measured voltage on transformer terminals reached the highest value, are presented. The total load power was 60 kW. Fig. 8 shows the voltage profiles for Feeder 1 (nodes 7 to 10), Feeder 2 (nodes 7 to 75), and Feeder 3 (nodes 7 to 61) for the initial case without any PV system installed. The node numbers in Fig. 8 are given along Feeders 1 to 3. The results presented clearly show that the loading of individual phases is unbalanced. Consequently, the L2 voltage in Feeder 2 reaches the lowest value close to the voltage limit.

The results presented in Figs. 9, 10 and 11 are obtained considering in section 2 described **approach I**, **approach II** and **approach III**, respectively. In all discussed cases, PV systems with a total power of 160 kWp are integrated into the grid using different approaches, where the results presented in Fig. 8 for the grid without any integrated PV system are the reference point.

Fig. 9 shows the results where PV systems with a total power of 160 kWp are installed on Feeder 1, representing PV system integration complying with **approach I**. The voltage profile in L1 on Feeder 1 reached the upper voltage limit, while the voltage profile in L2 on Feeder 2 was low. Using **approach I**, the potential for integrating additional PV systems into the grid is minimal, even when a transformer with an On Load Tap Changer (OLTC) is applied. The voltage in the Feeder 1 exceeded the upper limit, while the voltage in the Feeder 2 was close to the lowest limit. Moving the bus bar voltage up or down with the OLTC cannot solve the problem of exceeding voltage profile limits.

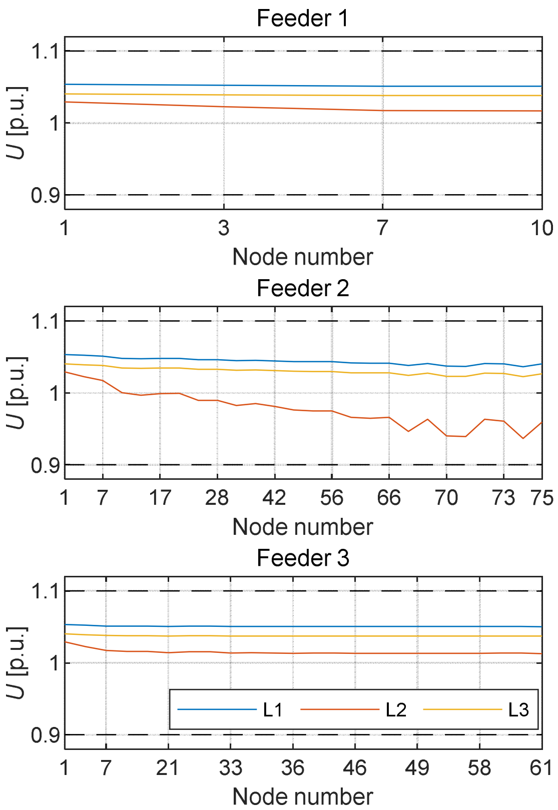

Fig.8. Voltage profiles along Feeders 1, 2 and 3 for the grid without any PV systems

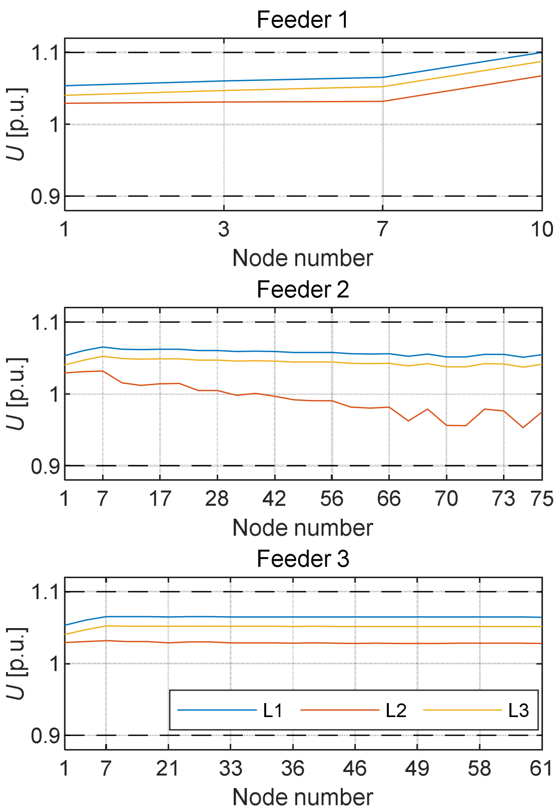

Fig.9. Voltage profile in Feeders 1, 2 and 3 for PV system integration into Feeder 1 according to approach I

Fig. 10 shows the results where 10 PV systems with a power of 16 kWp each and a total power of 160 kWp are installed on Feeder 3, representing PV system integration complying with **approach II**. The results are similar to those presented in Fig. 9. The voltage profile in L1 on Feeder 3 reached the upper voltage limit, while the voltage profile in L2 on Feeder 2 was low. Since the voltage profile on Feeder 3 exceeded the upper voltage limit, while the voltage profile on Feeder 2 approached the lowest voltage limit, the OLTC-equipped transformer cannot improve the voltage profiles to enable the integration of additional PV systems. However, results presented in Fig. 11, where PV systems with a total power of 160 kWp are evenly distributed on all three feeders (**approach III**), clearly show that the voltage profiles could be lowered with the OLTC-equipped transformer, which could enable the integration of additional PV systems into the grid.

The grid losses for the cases presented in Figs. 8 to 11 are summarised in Table I. The yearly energy exchange through the transformer and the yearly grid losses for the case without PV systems and the cases of PV systems integration into the grid according to approaches I, II and III are presented in Table II.

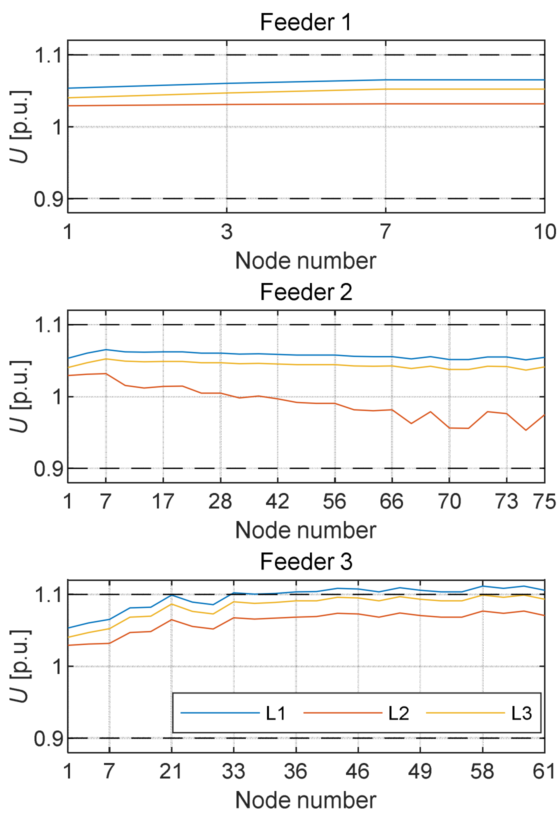

Fig.10. Voltage profile in Feeders 1, 2 and 3 for PV system integration into Feeder 3 according to approach II

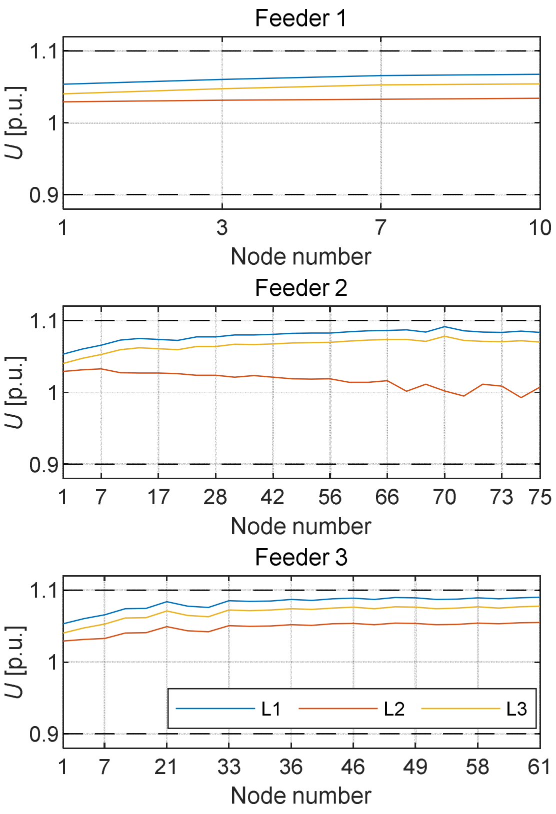

Fig.11. Voltage profile in Feeders 1, 2 and 3 for equally distributed PV system integration into Feeders 1, 2 and 3 according to approach III

Table I. – Grid losses for the total load of 60 kW

Case	Grid losses (kW)
No PV (Fig. 8)	2.26
Approach I (Fig. 9) one 160 kWp PV	9.36
Approach II (Fig. 10) 10 x 16 kWp PVs	9.50
Approach III (Fig. 11) distributed PVs	4.26

Table II. – Yearly energy transfer through the transformer and yearly grid losses without PV systems and with PV system integrated according to the approaches I, II and III

Case	Energy through the transformer (MWh)	Grid losses (MWh)
No PV	858.5	46.5
Approach I one 160 kWp PV	658.4	55,7
Approach II 10 x 16 kWp PVs	658.1	54,9
Approach III evenly distributed PVs	661.3	37.7

The results presented clearly show that distributed integration of PV system into the grid according to the **approach III**, not only enables integration of additional PV system in the grid but also reduces grid losses.

4. Conclusion

In the case study, the paper analyses how different approaches to integration of PV systems in distribution grids can influence the voltage profiles, grid losses, hosting capacity and behaviour of the PV systems' owners. The last statement will be addressed later.

At the early stage of PV systems integration into distribution grids in Slovenia, the approach I was used. Investments mostly in 50 KWp PV systems were motivated by support schemes. The increasing number of installed PV systems and support ten times exceeding the market energy prices led to the end of the support scheme after 2012, considering the presented results, with possible negative impacts on the provision of voltage profiles and grid losses.

The net-metering-based integration of PV systems into distribution grids, aligned with approach II, promoted yearly net self-sufficient energy supply under the misleading assumption that the grid can be considered energy storage. For the PV system owners, the fee for grid usage was reduced substantially. The contractors stimulated investments in PV systems that substantially exceeded energy consumption because they received a surplus of PV system produced energy for free. The consequences of investing in oversized PV systems are reduced hosting capacity, disabled integration of PV systems owned by other grid users, and excessive energy consumption. Nobody wants to deliver a surplus of PV system-produced energy to the grid for free. In addition to problems related to the provision of voltage profiles, grid losses and reduced hosting capacity, the net-metering motivated investment in PV systems changed the behaviour of PV system users towards excessive energy consumption, which is not following the European Green Deal [1]. Fortunately, the net-metering-motivated integration of PV systems reached its end.

Future research will build upon the insights provided in this paper. New investment strategies for PV systems and their integration into distribution grids should prioritize **approach III** outlined in this study. This approach advocates for incentivizing grid users to install suitably sized PV systems paired with energy storage systems. Additionally, mechanisms should be established to actively engage these investors in providing energy flexibility services, thereby fostering a more resilient and flexible grid.

Further advancements could focus on the establishment of local microgrids, with the goal of enhancing self-sufficiency in energy supply and potentially enabling limited island operations. These microgrids could serve as a crucial component in bolstering resilience and sustainability within communities, offering greater control over energy generation, distribution, and consumption.

Acknowledgement
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