Available online at www.sciencedirect.com

ScienceDirect

Energy Reports 8 (2022) 217–223

www.elsevier.com/locate/egyr

7th International Conference on Advances on Clean Energy Research, ICACER 2022 April 20–22, 2022, Barcelona, Spain

Congestion control strategies for increased renewable penetration of photovoltaic in LV distribution networks

Noman Shabbir[a,b,*], Lauri Kutt[a], Victor Astapov[a], Oleksandr Husev[a], Roya Ahmadiahangar[a,b], Fushuan Wen[a], Karl Kull[a]

[a] *Department of Electrical Power Engineering & Mechatronics, Tallinn University of Technology, Tallinn, 19086, Estonia*
[b] *FinEST Center for Smart Cities, Tallinn University of Technology, Tallinn, 19086, Estonia*

Received 5 October 2022; accepted 9 October 2022
Available online 25 October 2022

Abstract

Domestic photovoltaic (PV) installations are increasing their spread due to decreased cost, environmental friendliness, and relatively easy installation. However, the massive domestic PV deployment can bring the LV network (LV) distribution network to its sustained operating limits, as overvoltage and congestion can arise. The overvoltage problems can emerge due to reverse power flows and congestion can be caused if the installed PV capacity is higher than the distribution line loading capacity. The limitations of the LV networks arise especially during the seasons when domestic power demand is minimal, and PVs are generating at their peak. The research presented here incorporates a real suburban LV network with fifteen residential users. The measured load and PV generation data for one year are used to carry out power flow simulations. Several congestion leveraging strategies such as battery energy storage system (BESS) incorporation, reactive power control (RPC), and curtailment of peaks are discussed.

Peer-review under responsibility of the scientific committee of the 7th International Conference on Advances on Clean Energy Research, ICACER, 2022.

Keywords: Photovoltaic; Renewable energy; Congestion control; Hosting capacity; Battery energy storage systems

1. Introduction

The price of photovoltaic (PV) systems has decreased significantly in recent years [1]. The promotion of PV systems deployment has also increased due to their lower carbon footprint, clean energy production, and the deployment of nearly zero energy buildings (nZEBs) [2]. These rooftop PV installations are usually connected to the low voltage (LV) distribution network [3]. However, large-scale deployment of PV installations in LV networks can exceed the hosting capacity (HC) of the distributed energy generation [4], advising caution not to impose limitations

* Corresponding author at: Department of Electrical Power Engineering & Mechatronics, Tallinn University of Technology, Tallinn, 19086, Estonia.

E-mail address: noshab@taltech.ee (N. Shabbir).

https://doi.org/10.1016/j.egyr.2022.10.184

Peer-review under responsibility of the scientific committee of the 7th International Conference on Advances on Clean Energy Research, ICACER, 2022.

on network service. For example, high reverse power flows and reactive power disturbances can cause an increase in the voltage of the lines [5]. Rather often demand response (DR) and demand-side management (DSM) techniques are proposed as a solution, but they have also limitations to solve these LV grid problems [6].

The HC of the power lines is dependent on many factors such as installed PV rated power, load, load-to-feeder ratio, transformer rating [7], etc. The situation becomes problematic for the network operator when residential users install PV according to their own installed power targets, being often close to the point of common coupling (PCC) breaker installed rating. Due to the simultaneous PV input from multiple customers, grid operators are then required to upgrade transformers and distribution lines for uninterrupted grid operation according to the service quality standards. Without expensive upgrades, there could be few options to avoid overvoltage, congestion, and overloading problems in the network [8]. Overvoltage is a major concern for the grid operator and many solutions like reactive power control (RPC), on-load tap changer (OLTCs) and capacitor banks have been proposed [9,10]. Nowadays, power electronics switching converters, such as PV inverters, capabilities are increasing. For example, many PV inverters contain the RPC options. On the other hand, these can increase the harmonics in the network [11].

Overvoltage can be a greater issue in the suburban and rural grids, whereas in urban grids ampacity of lines is a major problem [12]. Distribution lines have a specific load rating designed to sustain operation under expected end customer loads and their coincidence expectations. However, excessive power from the multiple PV producers can lead to the overloading of the line components. Instead of upgrading the most potentially overloaded lines, a costly and time-consuming solution, several studies have proposed a BESS-based solution to overcome this problem [13].

This paper discusses different strategies for congestion control due to high PV infeed on the LV distribution network. The objective of the research is to increase the HC in the distribution lines while minimizing the grid congestion and overvoltage problem. A control strategy incorporating a BESS with a charging/discharging algorithm including market energy prices has been proposed. In addition, the capabilities risen by the deployment of the RPC technique have also been elaborated. The peak PV power curtailment has been discussed to refer to the impact of the discussed methods.

2. Case study of suburban grid

In this study, a line section of an Estonian suburban LV network containing a 0.4 kV distribution substation has been considered. This network has fifteen residential users and a total of thirteen distribution line sections. The schematic layout of the network is shown in Fig. 1. The load data of the residential users and the generation of photovoltaic energy assigned are based on measurements for the entire year, with a 1-hour time-step.

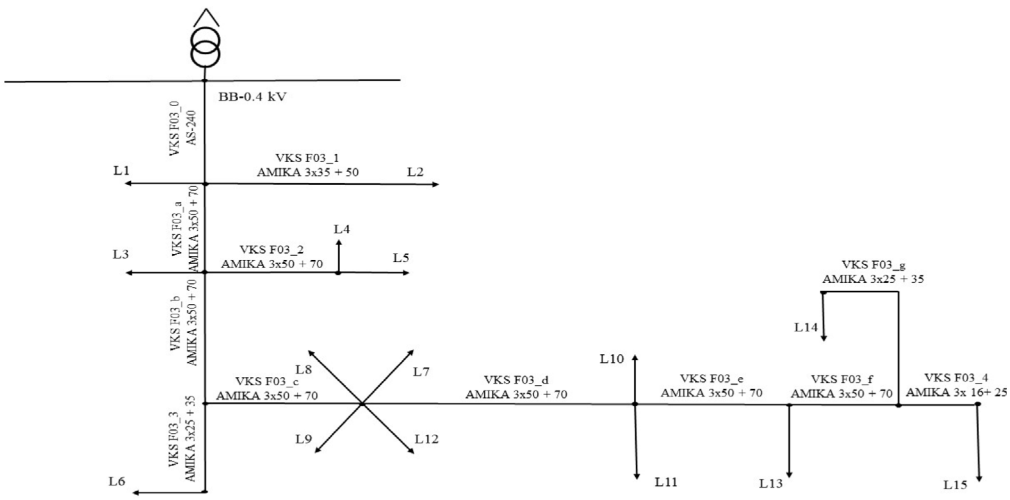


Fig. 1. Layout of the suburban grid under observation.

The transformer rating is 100 kVA and the rated value of the switch breaker is 100 A. The capacity of the cable AXMKA 3 × 50, from the largest part of the line constructed, is 140 A. The sum of the main fuses ratings in the feeder is 345 A. The assumption is that each customer installs PV according to the nominal values of the fuses, but slightly less than these marginal loads. When the switch breaker is 25 A then PV is rated at 20 A. For example, customer 1 has a 3 × 25 A connection, which means, that PV1 installed capacity would be 16 A or 11 kW. This way, the total installed capacity of 15 PV systems is 189 kW. The PV generation profile is taken from the data measured for the existing PV system connected to the nearby substation. The values were obtained by using the scaling factor, according to the nominal installed capacity of planning individual PV systems. A detailed description of the grid parameters is given in Table 1. The BESS sizes for all the residential users are calculated based on the peak load of the specific user using the following equation [14]:

$$E_{BC} = \frac{E_{Day}}{\eta * DoD * 1000} * N_d \tag{1}$$

where the E_{BC} is the BESS capacity (kWh), η is the BESS efficiency, N_d represents the number of days for which the BESS backup is required and is considered as 1 in our experimentation, DoD is the depth of discharge for the BESS, and E_{Day} is the peak energy usage of the customer on a day throughout the year (kWh).

Table 1. Grid parameters, rated PV powers, and the BESS sizes.

Load characteristics			PV	BESS parameters		Grid parameters			
Name in scheme	Average load (kW)	Peak load (kW)	Rated power (kW)	Capacity (kWh)	Charging power (kW)	Line section	Type of cable	Nominal current (A)	Length (m)
L1	0.6	3.0	13.8	31	3.8	VKS F03_0	AS-240	605	60
L2	0.6	3.7	11	25	3.1	VKS F03_1	AMKA.3 × 35 + 50	115	342
L3	0.1	0.7	11	25	3.1	VKS F03_2	AMKA.3 × 50 + 70	140	44
L4	0.5	6.6	4.2	10	1.3	VKS F03_3	AMKA.3 × 25 + 35	90	23
L5	0.6	5.8	11	25	3.1	VKS F03_4	AMKA.3 × 16 + 25	70	11
L6	0.4	3.1	13.8	31	3. 8	VKS F03_a	AMKA.3 × 50 + 70	140	45
L7	0.5	3.4	13.8	31	3.8	VKS F03_b	AMKA.3 × 50 + 70	140	79
L8	0.3	2.2	13.8	31	3.8	VKS F03_c	AMKA.3 × 50 + 70	140	38
L9	0.3	2.3	13.8	31	3.8	VKS F03_d	AMKA.3 × 50 + 70	140	38
L10	0.4	4.1	13.8	31	3.8	VKS F03_e	AMKA.3 × 50 + 70	140	44
L11	0.2	1.3	13.8	31	3.8	VKS F03_f	AMKA.3 × 50 + 70	140	39
L12	0.5	3.4	13.8	31	3.8	VKS F03_g	AMKA.3 × 25 + 35	90	102
L13	0.2	4.0	13.8	31	3.8	–	–	–	-
L14	0.7	4.2	13.8	31	3.8	–	–	–	-
L15	0.8	4.8	13.8	31	3.8	–	–	–	-

3. Congestion control strategies

3.1. Peak power curtailment

In this scheme, the maximum power generated by the PV panels is limited down to 70% and 50% [4,13] to overcome network congestion rather than cutting off the user altogether. The peak power is generated usually in the middle of the day and mostly in summer times when the residential loads are lowest. In this case, rather than injecting all the generated power, only a specific percentage is allowed into the grid. In this way, the PV energy peak is shaved off and as a result, the congestion in the network is leveraged as shown in Fig. 2(a). On the negative side, curtailing PV power will have an economic implication for all customers as the amount of energy sold to the grid will be limited.

3.2. Reactive power control (RPC)

The RPC mechanism can help in avoiding overvoltage problems in the network. The grid integrated PV systems most commonly inject active power into the grid and do not provide reactive power. However, due to power flow in the opposite directions at different times, excessive active power infeed and weak cross-sections of the lines could result in voltage fluctuations. The solution here is to use inverters with smarter functionality to absorb or generate reactive power when necessary. However, incorporating RPC in solar inverters can provide decreased efficiency and sometimes lead to increased harmonic distortions in the network. The results of RPC are shown in Fig. 2(b).

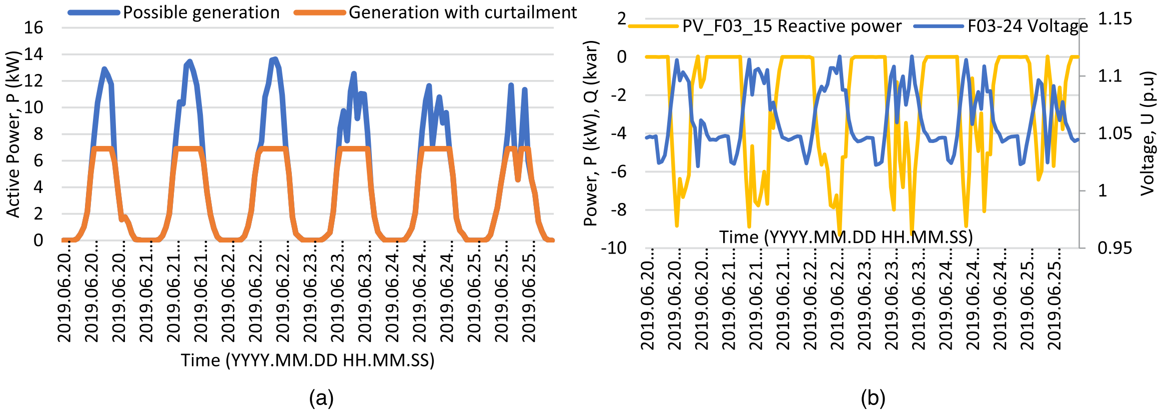


Fig. 2. (a) PV power curtailment (b) Reactive power control.

3.3. Congestion control with BESS

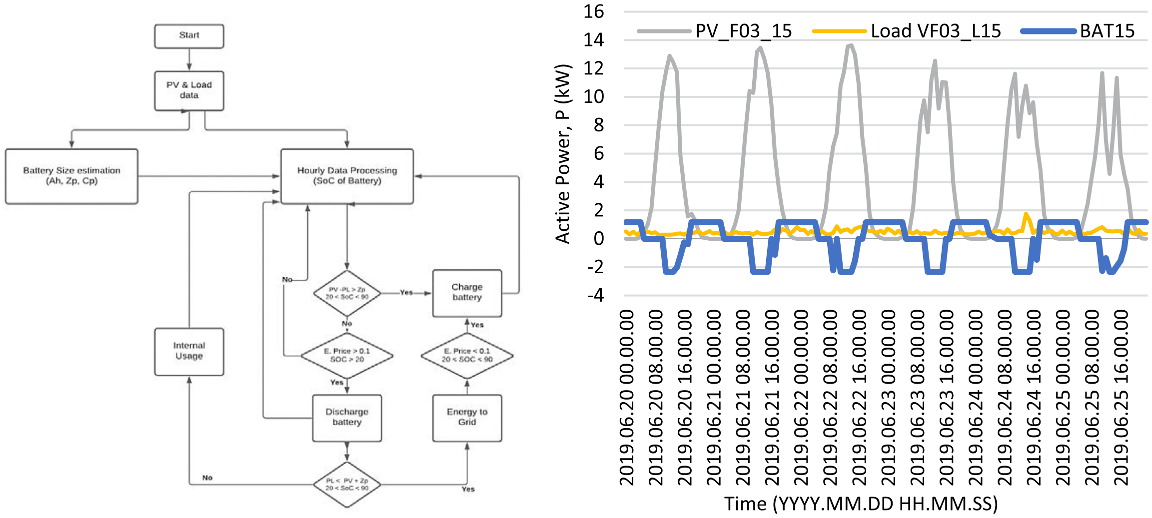
The inclusion of a residential BESS with the PV system may be a viable solution to overcome congestion. The main principle is to charge the BESS when PV is generating excessive energy and rather than injecting all the energy into the grid, a significant portion of that energy is stored in the BESS. Later, that energy can be used for domestic load or can be sold to the grid for monetary benefits. Therefore, this scheme can be feasible in terms of economic numbers compared to curtailment. The details of the heuristic BESS control algorithm are described in [5,14], the flow chart of the algorithm is depicted in Fig. 3(a) and the results are given in Fig. 3(b) for the load 15.

4. Results & discussions

The simulation results for the BESS profiles have been obtained using the heuristic algorithm implemented in Matlab. Meanwhile, the power flow analysis is carried out in DIgSilent Power Factory 2022. The results of the comparative analysis are shown in Table 2 presenting the total hour count for the whole year. The total number of hours in a year is 8760. The results are presented with the main evaluation outcome for the overloading of the lines and the network supply transformer. The overvoltage implies the situation only when the endpoint voltage result is higher than 1.1 p.u. (nominal voltage) values as described by the CENELEC-EN 50160 standard [15]. The standard indicates that the voltage on any node in the distribution network must not be greater or less than 10% of the nominal values but not more than 10 mins. The comparative analysis also shows the number of times in which any of the nodes had an overvoltage problem.

The initial results indicate that the considered photovoltaic installations, operated without control, cause severe overloading and overvoltage on the distribution lines for 556 and 1187 h in the year, respectively. The peak voltage value of 1.2 p.u violates the standard operating limits of the grid and it is entirely unacceptable to operate the grid. This is a major concern as it can cause problems in the residential appliances of the customers.

The PV curtailment to 50% peak power eliminates the overloading but still, the overvoltage problem exists. The incorporation of BESS significantly lowers these numbers to 15% and 76% of the non-control values. In addition, the peak values are reduced as well. The combination of BESS and RPC reduces the overvoltage, only to remain



(a) (b)

Fig. 3. (a) The flow chart of the BESS control algorithm (b) BESS control.

Table 2. Comparative analysis of all control strategies.

Condition	Number of times for all nodes	Number of hours	Max. value	Number of times for all nodes	Number of hours	Max. value
	Only PV (Initial Case)			PV + CURT. (6.9 kW)		
Transformer, overloaded	698	698	159	0	0	84
Lines, overloaded	1618	556	159	0	0	84
Nodes, U > 1.1 p.u.	15,919	1187	1.2	14,334	1212	1.14
	PV + BESS			PV + RPC + BESS		
Transformer, overloaded	170	170	134	891	891	191
Lines, overloaded	84	84	119	1748	796	175
Nodes, U > 1.1 p.u.	5868	880	1.18	2	2	1.10
	PV CURT. (6.9 kW) + BESS			PV CURT. (10 kW) + RPC + BESS		
Transformer, overloaded	0	0	97	870	870	180
Lines, overloaded	0	0	92	1065	575	170
Nodes, U > 1.1 p.u.	1539	360	1.14	0	0	1.10

for a span of 2 h. However, the overloading of the lines and the transformer is increased, and the peak values are also higher. BESS plus curtailment of PV generation to 6.9 kW (50%) per user can reduce the overloading to zero, but the overvoltage is remaining for 360 h.

5. Conclusions

Different options have been evaluated here to mitigate the congestion and overvoltage problems that can occur in the LV distribution network due to the excessive PV installations by residential customers. Reaching the installation power rating ceiling is more and more probable due to the encouragement by governments and environmental organizations. Reaching the hosting capacity limits is more likely when the customers have the liberty to install as much PV power as they desire and then connect it to the grid. At first glance, this is good for the environment and customers in terms of monetary benefits. However, this can create a serious problem in the electrical grid, and it can become difficult for the operator to keep the grid running within the limits defined in the standards. If the latter terms are violated, no one can access the grid for PV infeed in any case, dismissing the initial noble intentions.

Requiring customers to reduce or turn off their photovoltaic injection to the grid would need to meet the same service terms for all parties connected to the grid. Therefore, utilities would often prefer to upgrade and reinforce their distribution line in most scenarios. However, the full upgrade would also likely impose limitations and is costly. Therefore, in this study, some localized solutions for congestion control are proposed and their expected effects are discussed. For example, if some specific high-PV infeed customers would be needed to provide specific functionality in addition to the PV production capabilities, the utility could be leveraged from the most expensive upgrades. In such a case, the higher PV infeed capability would also mean greater responsibility for the customer.

The results indicate that the reduction in PV generation power alone is not a good solution to congestion control. The integration of BESS can drastically reduce this congestion drastically; however, it would not be sufficient to eliminate overvoltage problems to acceptable margins. However, in conjunction with voltage control and slight curtailment of the PV systems, the proposed algorithm shows much better results from the grid operation perspective together with the utilization ratio at 96%. The economic implication of these schemes can be explored further in future work.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgments

This work was supported by Estonian Research Council grants PRG675, PSG739, and European Commission through H2020 project FinEST Twins grant No. 856602. The measurement data was taken from the project LEEEE20025.

References

[1] Rahmat Khezri, Amin Mahmoudi, Hirohisa Aki. Optimal planning of solar photovoltaic and battery storage systems for grid-connected residential sector: Review, challenges and new perspectives. Renew Sustain Energy Rev 2020;153:111763. http://dx.doi.org/10.1016/j.rser.2021.111763.

[2] Toomas Vinnal, Hardi Puusepp, Noman Shabbir, Naveed Iqbal Muhammad. Case study of non-linear PV inverter devices attached to the LV distribution network. Agron Res 2020;18(4):2639–52.

[3] Noman Shabbir, Muhamamd Usman, Muhamamd Jawad, Haseeb Zafar Muhamamd, Naveed Iqbal Muhammad, Lauri Kütt. Economic analysis and impact on national grid by domestic photovoltaic system installations in Pakistan. Renew Energy 2020;153:509–21. http://dx.doi.org/10.1016/j.renene.2020.01.114.

[4] Walter Niederhuemer, Roman Schwalbe. Roman increasing PV hosting capacity in LV grids with a probabilistic planning approach. In: Proc. - 2015 Int. Symp. Smart Electr. Distrib. Syst. Technol. EDST 2015, (2015). 2015, p. 537–40. http://dx.doi.org/10.1109/SEDST.2015.7315266.

[5] Noman Shabbir, Lauri Kütt, Victor Astapov, Kamran Daniel, Ashraf Raja Hadi, Naveed Iqbal Muhammad, Husev Oleksandr. Feasibility investigation for residential battery sizing considering EV charging demand, Sustain 14(3). http://dx.doi.org/10.3390/su14031079.

[6] Mohamamd Moktadir Rahman, Ali Arefi, Mohammad Shafiullah Hulam, Sujeewa Hettiwatte. A new approach to voltage management in unbalanced low voltage networks using demand response and OLTC considering consumer preference. Int J Electr Power Energy Syst 2017;99:11–27. http://dx.doi.org/10.1016/j.ijepes.2017.12.034.

[7] Ali Arshad, Martin Lindner, Matti Lehtonen. An analysis of photo-voltaic hosting capacity in finnish low voltage distribution networks. Energies 2017;10(11). http://dx.doi.org/10.3390/en10111702.

[8] Sameen Fatima, Verner Püvi, Matti Lehtonen. Review on the PV hosting capacity in distribution networks. Energies 2020;13(18). http://dx.doi.org/10.3390/en13184756.

[9] Tom Verschueren, Kevin Mets, Bart Meersman, Matthias Strobbe, Chris Develder, Lieven Vandevelde. Assessment and mitigation of voltage violations by solar panels in a residential distribution grid. In: 2011 IEEE Int. Conf. Smart Grid Commun. SmartGridComm 2011. 2011, p. 540–5. http://dx.doi.org/10.1109/SmartGridComm.2011.6102381.

[10] Tariq Aziz, Nipon Ketjoy. PV penetration limits in low voltage networks and voltage variations. IEEE Access 2017;5:16784–92. http://dx.doi.org/10.1109/ACCESS.2017.2747086.

[11] Anamika Dubey. Impacts of voltage control methods on distribution circuit's photovoltaic (PV) integration limits. Inventions 2017;2(4). http://dx.doi.org/10.3390/inventions2040028.

[12] Bryan Navarro, Maricar Navarro. A comprehensive solar PV hosting capacity in MV and LV radial distribution networks. In: 2017 IEEE PES Innov. Smart Grid Technol. Conf. Eur. ISGT-Europe 2017 - Proc. 2017, p. 1–6. http://dx.doi.org/10.1109/ISGTEurope.2017.8260210.

[13] Andreas Procopiou, Luis Ochoa. Asset congestion and voltage management in large-scale MV-lv networks with solar PV. IEEE Trans Power Syst 2021;36(5):4018–27. http://dx.doi.org/10.1109/TPWRS.2021.3067838.

[14] Noman Shabbir, Kütt Lauri, Astapov Victor, Jawad Muhammad, Alik Alo, Husev Oleksandr. Battery size optimization with customer PV installations and domestic load profile. IEEE Access 2022;10:13012–25.

[15] Noman Shabbir, Lauri Kütt, Marek Jarkovoi, Iqbal Muhammad N, Anton Rassõ, Kamran Daniel. An overview of measurement standards for power quality. Agron Res 2021;19(Special Issue 1):944–60. http://dx.doi.org/10.15159/AR.21.074.