Limitations of Overvoltage Mitigation Methods in High PV Penetration LV Distribution Networks

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2024 IEEE Kansas Power and Energy Conference (KPEC) | 979-8-3503-7240-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/KPEC61529.2024.10676197

***Abstract*—The surging integration of Photovoltaic (PV) systems in low-voltage networks promises increased self-consumption and reduced energy costs, but its rapid adoption introduces new challenges. The inherently stochastic nature of demand and PV generation can lead to scenarios in which excess PV energy is injected into the network, causing potentially critical overvoltage issues. This paper investigates the limitations of three prevalent overvoltage mitigation methods: inverter tripping, fixed feed-in power limitation, and droop-based active power curtailment. The efficacy of each method in maintaining voltage stability is investigated to expose underlying drawbacks such as curtailment of valuable renewable energy, operational complexities, unfairness, and potential network instability under specific scenarios.**

***Index Terms*—Low voltage distribution network, self-consumption ratio, overvoltage mitigation, active power curtailment.**

I. Introduction

The adoption of distributed energy resources (DER) by residential, commercial, and industrial facilities has increased dramatically. The main reasons for this massive proliferation of DER, particularly PV systems, are increasing self-consumption, reducing energy bills, and gaining economic benefits via energy arbitrage. Integrating grid-connected PV systems enables a significant mix of renewable energy to the grid. However, the conventional power grids are designed to serve the customers by unidirectional power flow from the upstream feeder to the downstream load. Therefore, the bidirectional power flow introduces new challenges to the grid, especially at the low voltage level due to the high resistance to reactance ratio. These challenges include overvoltage issues, reverse power flow, and increased power losses, which lead to grid instability in low-voltage distribution networks (LVDN). Overvoltage undeliberately triggers the protection relays, isolating the feeder from the LVDN. The likelihood of overvoltage occurrence depends on various parameters, such as the feeder impedance and the mismatch between the PV generation and the load [1], [2].

Traditionally, the overvoltage issue is tackled by restricting the feeder DER hosting capacity to conservative limits. For example, in some countries, the installation of DER is limited to only 15% of the distribution transformer in the LVDN [3]. Nevertheless, this leads to the underutilization of renewable energy potential. Other overvoltage mitigation methods include inverter tripping, adjusting the transformer ratio to decrease the secondary voltage, reducing power cable impedance by expanding the conductor size, setting a fixed feed-in power limitation, online load tap changing transformer, reactive power compensation, and grid reinforcement [4]–[6]. One of the significant features of the LVDN is the high resistance-to-reactance, which makes the voltage highly sensitive to active power fluctuations. Thus, using reactive power compensation is not fully effective in LVDN. Conversely, active power control methods effectively reduce overvoltage [5]. Furthermore, energy storage systems (ESS) can play an essential role in preserving grid stability by storing the surplus energy from the DER and using it in peak load periods [7].

This paper investigates three widely used methods to secure power grid stability: inverter tripping, fixed feed-in power limits, and droop-based active power curtailment (APC). The impact of these methods on the grid voltage and energy curtailment will be discussed. The Python-based power system simulation tool Pandapower [8] is used to carry out the analysis.

II. OVERVOLTAGE MITIGATION METHODS

The IEEE European Low Voltage Test Feeder is used to conduct the analysis. The test feeder has 906 nodes with 55 active nodes, as illustrated in Fig. 1. It is assumed that all the customers in this LVDN are prosumers equipped with PV systems and the installed capacity is distributed among the consumers based on their demand. PV capacity varies from 1 kW up to 19.6 kW, and the self-consumption ratio (SCR) varies between 4.9% and 84.1%, averaging 27.5%. Moreover, the secure voltage operation range of the LVDN is 0.94-1.1 pu, and the nominal voltage is 1.05 pu. The SCR is the ratio between the part of the PV generation directly transferred to the load and the total PV generation, as stated in Eq. (1).

$$SCR = \frac{\int_{t=0}^{T} P_t^{pv \to load}}{\int_{t=0}^{T} P_t^{pv}} \tag{1}$$

where $P_t^{pv} = P_t^{pv \to load} + P_t^{pv \to grid} + P_t^{pv \to curtailed}$

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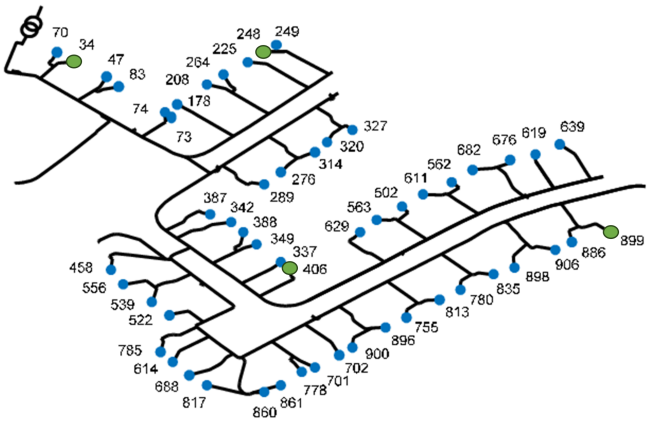


Fig. 1. The single-line diagram of the IEEE European LVDN Test Feeder [9]

A. Inverter Tripping Method

The conventional inverters trip if the voltage at the point of common coupling (PCC) surpasses the critical voltage limit and reconnects to the grid after a time delay [6]. Since the overvoltage occurs at the nodes that are distant from the transformer, the prosumers at the end of the feeder become disadvantaged because of their physical location [10]. However, this control method does not require communication infrastructure between prosumers, so it depends on local control.

B. Fixed Feed-in In Power Limitation

The distribution system operators may impose maximum feed-in power limits to avoid the possible technical issues of high PV penetration. The maximum feed-in power limits are calculated based on the installed capacity. For instance, in Germany, there is no limitation for hosting capacity in the feeders; however, the prosumers must limit their power injection to the grid by 70% of their installed PV capacity [11]. It is worth mentioning that the feed-in limits do not consider the grid dynamics, such as supply, demand, or voltage fluctuations. Instead, it only limits the surplus power. Thus, it might lead to underutilization of green energy in some periods due to unnecessary curtailment, and it also does not guarantee that the operation will be within the voltage safety range. This paper assumes that the prosumers cannot inject more than 40% of their installed PV capacity into the grid [12].

C. Droop-Based Active Power Curtailment

The correlation between voltage and active power is stronger than with reactive power in the LVDN due to the resistive nature of the power lines. Therefore, droop-based APC might be another method to reduce overvoltage in the network. This method does not require shared information among prosumers and can be controlled locally. The active power injection is limited based on the current state of the voltage (V_{pcc}) as given in Eqs. (2) and (3) [6].

$$P_{inj} = \begin{cases} P_{mppt} - m * max(0, V_i - V_{cri}), & V_{cri} \leq V_i \leq V_{max} \\ 0, & V_{cri} \geq V_{max} \end{cases} \tag{2}$$

$$m = \frac{P_{mppt}}{V_{max} - V_{cri}} \tag{3}$$

where, P_{inj} is the injected power (kW), m (kW/V) is the droop coefficient as given in Eq. (3), V_{pcc} ,V_{cri} ,V_{max} are the voltage at PCC, a preset critical voltage, and the maximum voltage in the LVDN, respectively. When the voltage at PCC operates within the normal range, no energy curtailment takes place. However, once the voltage surpasses the critical limit, power injection begins to be gradually curtailed. Injection is completely prevented when the voltage exceeds the maximum operational limit. To our knowledge, no study had specified V_{cri} value for the IEEE European Low Voltage Test Feeder. In studies [13] and [14], the critical voltage is 1.05 pu, and 1.042 for a suburban network in Canada, respectively. Considering these studies, and the nominal and maximum voltages, it is assumed that V_{cri} equals 1.085 pu in our benchmark.

III. SIMULATION RESULTS

For the case study considered in this paper, prosumers do not have dispatch flexibility. Thus, all the surplus power is either injected into the grid or curtailed. Four methods are implemented: uncontrolled grid injection, droop-based APC, inverter tripping, and feed-in power limitations. Fig. 2. illustrates a comparative analysis of four methods to deal with

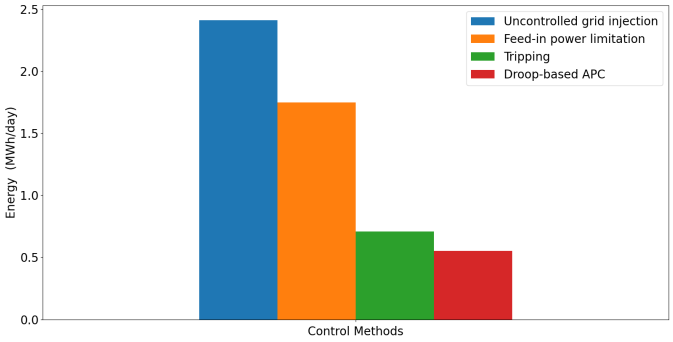


Fig. 2. Energy grid injection under different control methods

the surplus PV energy conveyed to the distribution network. Uncontrolled grid injection means that all the surplus energy is injected into the grid unconditionally. All the excess energy (2.4 MWh) is injected into the grid in this scenario. Second, feed-in power limitation signifies a strategy for deliberately reducing or curtailing energy injection. This strategy restricts the power injection by the installed PV capacity. This paper assumes that the prosumers cannot inject more than 40% of their installed PV capacity into the grid. It enables power injection to the grid regardless of supply and demand conditions; thus, voltage violations might occur. Under this method,

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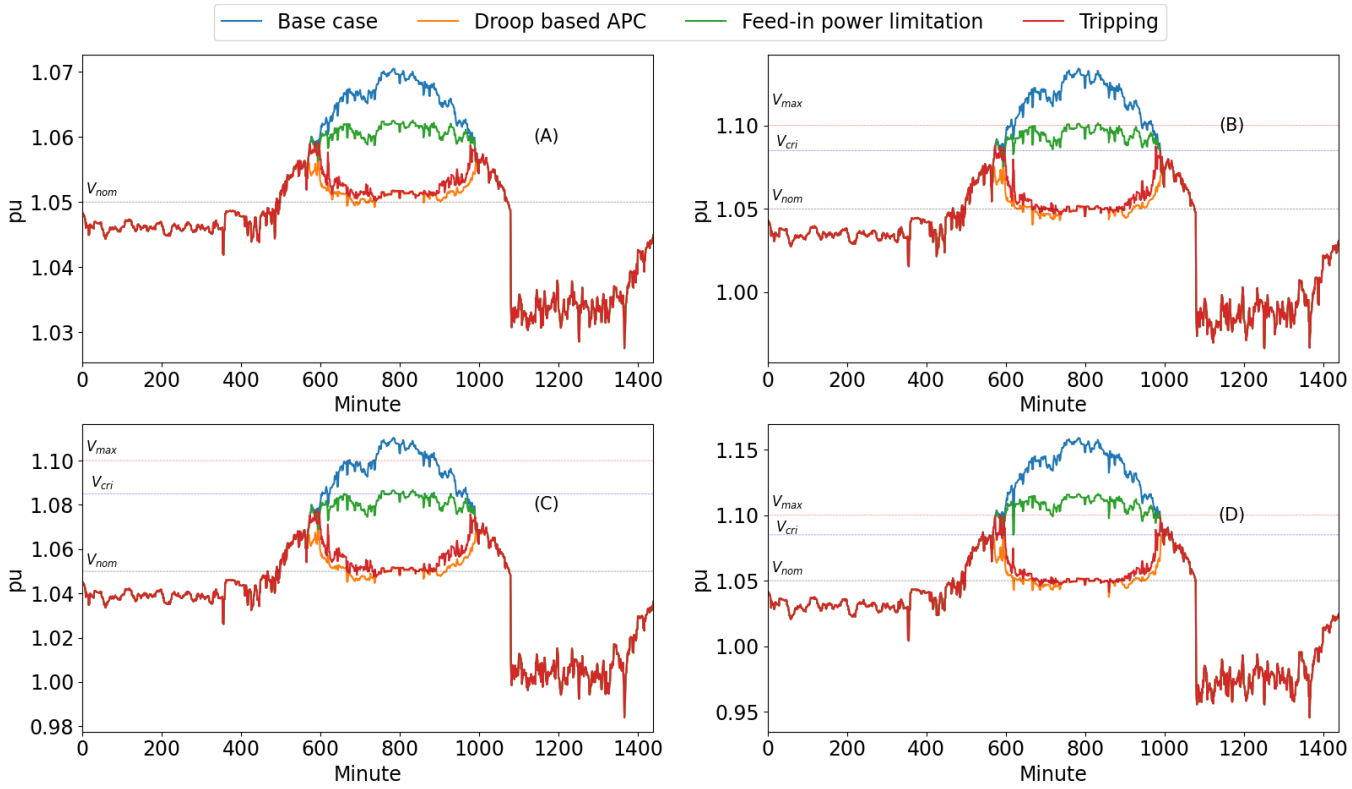


Fig. 3. The resultant voltage after applying active power control methods at (A) bus 34, (B) bus 248, (C) bus 406, and (D) bus 899.

72.8% of the surplus energy is injected into the grid. The Inverter tripping method, moreover, disconnects the inverter from the grid in case of an overvoltage issue. Thus, this method generally leads to high power curtailment compared to other methods. Here, only 29.4% of the energy is injected into the grid. Lastly, the droop-based APC method ensures voltage within the predetermined safety range, leading to the highest energy losses. This method injects 23% of the excess energy into the grid.

Fig. 3 compares the voltage in the base case (without an active power control mechanism) and the three control techniques. Four buses are selected to conduct the analysis considering their distance from the substation: bus 34, bus 248, bus 406, and bus 899, respectively. At bus 34, as shown in Fig. 3(a), the voltage doesn't exceed the maximum operation condition (1.1 pu). Therefore, there is no energy curtailment in the case of droop-based APC and tripping methods. The voltage under these methods drops to 1.05 pu due to the curtailment at the other buses. Considering the 40% feed-in power constraint, 18.6 % of the surplus power is curtailed from the prosumer at bus 34. The highest voltage occurs to be 1.063 in the feed-in power method. Similarly, as we move further from the transformer, the voltage rises, and the highest voltage in the system (1.116 pu) occurs at noon at bus 899 under the feed-in power method.

The energy curtailment at the selected buses after applying active power control methods is given in Table I. The total

TABLE I
ENERGY CURTAILMENT RATES BY POWER CURTAILMENT METHODS

	Energy Curtailment over Total Solar Generation			
Methods	Bus 34	Bus 248	Bus 406	Bus 899
Feed-in power	18.6%	6%	17.7%	22.4%
Tripping	0%	21.9%	56.4%	62.2%
Droop-based APC	0%	27.5%	61%	62.5%

solar generation on bus 34 is 40 kWh. After using the Feed-in power constraint, the usable solar generation has dropped to 32.4 kWh. It can be observed from Fig 3. that the voltage at bus 34 is below 1.08 pu; thus, the inverter remains connected to the grid. This case leads the solar generation at bus 34 to be the same as the base case, without curtailment when tripping and droop-based APC methods. However, the voltage drops at bus 34 due to the curtailment at different buses, especially the ones at the end of the feeder. For the buses 248, 406, and 899, the total generation is 20.5 kWh, 58.2 kWh, and 100 kWh, respectively. The curtailed energy at the three buses due to droop-based APC is more than tripping because the curtailment starts when the voltage is in the critical band.

IV. DISCUSSION

The three overvoltage prevention methods discussed in this paper are technically evident to be effective in mitigating the rise in voltage. However, each method presents its limitations. Droop-based APC and tripping, in common, introduce un-

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TABLE II
COMPARISON OF THE POWER CURTAILMENT METHODS*

Methods	Ensure voltage stability	Requires Communication Link	Fairness	Energy Curtailment
Feed-in power	No	No	Moderate	Low
Droop-based APC	Yes	No	Poor	High
Tripping	Yes	No	Poor	High

* Note that this comparison was conducted between these three methods solely for the specific case study.

fairness between the prosumers due to varying curtailments due to their location in the LVDN. For example, the SCR of the prosumer at bus 34 is 30.8%, and it injects 100% of the surplus power into the grid. Meanwhile, the prosumer at bus 248 has a higher SCR (55.6%). However, it injects only 38% and 50.6% of the total surplus power under droop-based APC and tripping, respectively. If the financial benefits of injection, such as feed-in-tariff, are considered, the prosumer with higher injection would benefit more than the others. Table II shows the advantages and drawbacks of each power curtailment method. While the discussed overvoltage prevention methods demonstrate effectiveness, their limitations necessitate exploring fairer and more comprehensive solutions. Droop-based APC and tripping unfairly impact prosumers based on location, hindering some from fully contributing despite higher SCRs. New methods are crucial to effectively address overvoltage while ensuring fairness and maximizing prosumer contribution. These methods should prioritize fairness, value self-consumption, and holistically consider each prosumer's contribution, independent of their location within the feeder.

V. CONCLUSION

The increasing integration of renewable energy sources, particularly PV systems, in the LVDN, has led to a new era of sustainable electricity generation. However, this transition has its challenges. One of the most pressing concerns is the occurrence of overvoltages in LVDN, which can pose a significant threat to the stability and reliability of the power grid. This paper investigates three active power control methods: droop-based APC, tripping, and feed-in power limitation. The results reveal that while the former two methods ensure voltage stability, the feed-in power limit does not consider voltage in the methodology, which may lead to situations where there is overvoltage at the end of the feeder. Furthermore, droop-based APC and tripping methods restrict the power injection conservatively, which may cause unnecessary renewable energy loss. The significance of these methods is in their implementation simplicity because they do not require any communication among the prosumers or the system operator due to their dependence on local control. On the other hand, they introduce unfairness and potentially less revenue depending on the prosumer's location in the network. Thus, considering the rapid growth of DER, developing more flexible and fair control methods has become indispensable.

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