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Regulation strategies for mitigating voltage fluctuations induced by photovoltaic solar systems in an urban low voltage grid

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ABSTRACT

Transient clouds cause rapid changes in the power output of Photovoltaic (PV) solar systems. These ramp rates may lead to power quality problems, such as voltage fluctuations, in the low-voltage (LV) electricity grid. This paper firstly assesses the impact of a growing number of distributed PV systems on the voltage profile in a LV grid by considering PV penetration rates of 40%, 70% and 100% of the local rooftop capacity. Next, the potential of active power curtailment, grid reinforcement and supercapacitors to prevent or mitigate these voltage fluctuations are examined. The experiments in this study are based on simulations run with a two-second time resolution for an urban LV grid located in Utrecht, the Netherlands. This study identifies that problematic fluctuations occur already at a 40% PV penetration rate and are expected up to 7.4% of time for a 100% PV penetration scenario. Additionally, the local deployment of either active power curtailment or supercapacitors are identified as adequate strategies to regulate the occurring voltage fluctuations. Finally, the most stable voltage profile and the lowest number of problematic voltage fluctuations are found in case of adopting supercapacitors as part of the PV system.

1. Introduction

In the past decade, a rapid increase in solar Photovoltaic (PV) capacity is observed at a global level [1]. By the end of 2020, the installed capacity was estimated at 714 GWp [2]. Moreover, with an added annual capacity of 127 GWp, solar PV was the quickest growing renewable power generation technology in 2020 [2]. Due to further decreasing costs, it is expected that this trend will continue and the global installed solar PV capacity is foreseen to at least triple in this decade [3]. This growing capacity will have an impact on the current electricity system and affect its operation.

The power output of a PV system is directly dependent on the solar irradiance that is received in the plane of the PV array. Shading caused by transient clouds can therefore lead to major changes in the power output in mere seconds. Previous studies have identified that these power fluctuations, i.e. ramp rates, can result in a power increase or drop of up to 90% of the rated capacity per minute [4–6] and up to 66% per 10 seconds [6,7], which is partly due to cloud enhancement effects [8]. Although the voltage in the distribution grid is through standards and regulations allowed to vary over time within certain limits [9], ramp rates may cause power quality problems in the form of voltage swings. Moreover, voltage fluctuations are identified as most problematic at the distribution grid level [10,11] and can damage both the local electricity grid as well as the appliances connected to the grid. Furthermore, these fluctuations could result in health related problems [12]. Consequently, to maintain the power quality in the electricity grid at all times, various standards have been set (e.g. NEN-EN 50160 [13], IEC 61000-4-15 [14] and the ‘Dutch Grid Code’ [15]).

In 2019, about 73% of the installed PV capacity in Europe was connected directly to the distribution grid [16]. Similarly, over half of the expected growth in PV capacity is expected from distributed, i.e. rooftop and small commercial, PV systems [3,16]. In addition to distributed PV, a significant amount of utility scale PV may be connected to the distribution grid, as the low (LV) and mid (MV) voltage grids host single connection capacities up to 0.3 and 10 MW in the Netherlands [16,17]. As a result, the impact of PV related ramp rates on the power quality in the distribution grid will grow, leading to increased voltage fluctuations in especially the LV grid, putting

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pressure on the grid standards set [5]. This observation is also reported in [9,18,19].

Traditionally, power quality problems like voltage fluctuations in the LV grid are dealt with through grid reinforcement, i.e. strengthening the LV grid [17,20]. By reinforcing the grid, voltage fluctuations are reduced because of an increased capacity and reduced resistance of the LV grid cables. Nevertheless, this voltage regulation method is costly, requires replacement of many LV cables and is therefore identified as undesirable [21]. Previous studies have identified and assessed other strategies that can be adopted or deployed in the LV grid to prevent or mitigate voltage fluctuations associated with the ramp rates from PV systems.

The first alternative strategy concerns the installation of Electrical Energy Storage (EES) in the LV grid. EES can be deployed by charging and discharging an EES device, to react to sudden changes in the power output of a PV system [22–24]. From all EES alternatives, only batteries and supercapacitors are deemed adequate for the purpose of voltage regulation, since these have the technical ability to react to voltage fluctuations within seconds [14] and can be placed throughout the LV grid [25,26]. Moreover, in comparison to batteries, e.g. lead acid or lithium ion, supercapacitors have a higher power density and faster response time, subsequently supercapacitors are technically more suitable for the purpose of mitigating rapid voltage fluctuations. Hybrid battery-supercapacitor applications that mitigate slow and fast voltage fluctuations due to variable solar PV production are proposed in [27,28]. These studies conclude that supercapacitors are capable of mitigating rapid voltage fluctuations.

The battery of an Electric Vehicle (EV) could also be adopted to mitigate voltage fluctuations in the LV grid [29]. The technical potential of voltage regulation by means of EVs was successfully tested before [29–31]. Nevertheless, the usage of EVs to this purpose requires them to be connected to a charging point in the LV grid, charging points and EVs that allow for bi-directional power flows, EV drivers to agree on participation, and availability of the EV battery to be charged or discharged, which may conflict with the needs of the EV driver. Consequently, these dependencies deteriorate the potential usage of EVs for voltage regulation purposes.

Another method that can be deployed for voltage regulation is power curtailment [22]. Curtailment can be employed to actively limit the power output of a PV system by adjusting the operating voltage and current in the systems' inverter [32]. This should limit the power output of a PV system when the inverter experiences a quick surge in its power output. Besides, it could uniformly limit the power output during the lead time prior to the occurrence of an expected drop. Broadly, all curtailment strategies can be divided into two categories, namely static and dynamic [33]. In static curtailment, the power output is limited to a predefined and fixed threshold based on the observed ramp rate. On the other hand, the dynamic method relies on the measured voltage fluctuations to activate the curtailment of power. Consequently, in the latter approach, power is only curtailed when voltage fluctuations become critical, such that this method is more effective and results in less curtailed power [33]. In [32], active power curtailment is successfully applied in the LV grid to mitigate voltage fluctuations caused by distributed PV systems.

Other methods that can regulate the voltage level are reactive power control and the deployment of tap changers [34,35]. However, in the LV grid and especially in an urban LV grid, the potential of reactive power control is limited due to the relative short cable length [17,26]. Similarly, tap changers are considered to be inadequate as these can only regulate voltage fluctuations near the transformer substation [24], whereas fluctuations from PV power generation are found most problematic at the other end of the cable [29].

In the current literature, most studies evaluate the potential of a single method to regulate voltage fluctuations [24,28,29,31,35]. Besides, many studies [20,21,23,24,28,35] consider a relative low temporal resolution, while PV power output ramp rates occur in the order of seconds with the consequence of causing problematic voltage fluctuations in the same time span. Besides, the number of studies that use actual data and simulate the impact of introducing one of these voltage mitigation strategies on the voltage levels in the grid is limited.

Few studies are found that compare the adequacy of the above mentioned voltage regulation strategies amongst each other in a case study [21,33,36]. In [21] a chiefly economic assessment among different voltage regulation strategies that consider reactive power control, curtailment and grid reinforcement, was performed for a suburban grid in Germany. An elaborate study, comparing methods and suitability of different regulation techniques, including grid reinforcement and active power curtailment, was performed in [33]. However, in this study emphasize was laid upon preventing over-voltage. The authors in [36] investigated how EES and curtailment can be used to limit power fluctuations, but did not discuss the effect on the voltage profile. Overall, there is a lack of studies that compare the potential of voltage regulation techniques to control the voltage level in urban LV grids with a high PV penetration rate and particularly of such studies that consider a high temporal resolution.

The goal of this study is to compare the technical potential of those solutions that are deemed as practically feasible and desired to be deployed to regulate voltage fluctuations in an urban LV grid. Hence, the paper firstly aims to identify the extent of the problem of voltage fluctuations with an increasing PV penetration rate. For this purpose, this study utilizes measured PV power output data with a two-second resolution. Next, the voltage fluctuation mitigation potential of three different solutions is tested, namely: (i) active power curtailment, (ii) grid reinforcement and (iii) supercapacitors. Consequently, the results of this research contribute to understanding the potential impact of voltage fluctuations in the LV grid. Furthermore, this research provides insights in the mitigating effect that active power curtailment, grid reinforcement and supercapacitors can have on voltage fluctuations. This information can be deployed by Distribution System Operators (DSOs) to determine how much voltage regulation capacity should be available in the future and what strategy can be adopted to prevent or mitigate problematic voltage fluctuations.

This paper proceeds as follows. Section 2 discusses the methods and explains the voltage regulation strategies. In Section 3 the system design is presented, including the grid lay-out and simulated power flows. Next, the results are presented in Section 4. Finally, in Section 5 the main findings of this study are concluded.

2. Methods

In order to illustrate the efficacy of the voltage mitigation strategies, this section firstly explains the components that affect the voltage. Secondly, problematic levels of voltage fluctuations are identified. In addition, this section presents and discusses the voltage fluctuation mitigation strategies, i.e active power curtailment, grid reinforcement and supercapacitors, which are examined in this study. Finally, it shows how the experiments are run.

2.1. Voltage fluctuations

Voltage fluctuations are described as random temporal variations in the voltage level observed in the electricity grid. The observed fluctuation at a certain point and time depends on the resistance R [Ω] within the circuit, the receiving end voltage V_R [V], the inductive reactance X [Ω], the active power P [W] and the reactive power Q [var]. Moreover, the relation between the voltage fluctuations ΔV [V] and its dependencies are described by Eq. (1) [22].

$$|\Delta V| = \frac{R}{V_R} dP + \frac{X}{V_R} dQ. \tag{1}$$

In an existing grid, the resistance, receiving end voltage and inductive reactance act as constants. Thus, only the active and reactive power change over time. In an urban LV grid the R/X ratio is generally high due to the relative short length of the grid cables [17, 26]. Consequently, $\frac{R}{V_R}dP$ in Eq. (1) becomes dominant and therefore has a higher potential on modifying the magnitude of the voltage fluctuations. Hence, this research only includes voltage regulation techniques that can adjust parts of $\frac{R}{V_R}dP$ in Eq. (1) and excludes others, e.g. reactive mitigation strategies, as these cannot fulfill this objective.

2.1.1. Threshold

This research quantifies thresholds for the allowed voltage fluctuations based on an extensive study by [37] in which the authors measured at what frequency and extent of voltage fluctuations, the fluctuations became visible and irritating for a broad group of subjects. Because this study uses solar PV data with a two-second resolution, see Section 3.4, the quantified thresholds are considered for this temporal resolution. Moreover, on a two-second resolution a voltage fluctuation threshold of 0.36% is defined for fluctuations to be visible and 0.84% for it to be classified as irritating [37]. For example, in case of a visible fluctuation, this threshold is violated if there is an absolute voltage drop or raise from one to the consecutive time step that surpasses 0.36% of the operating voltage. Considering a nominal voltage of 230 V, at which the LV grid in the Netherlands is operated [17], this corresponds to a voltage change of 0.83 and 1.92 V per two-seconds (ΔV/2s) for the fluctuations to be classified as visible and irritating, respectively.

2.2. Mitigation strategies

2.2.1. Active power curtailment

Active power curtailment aims to prevent the occurrence of voltage fluctuations by limiting the active power output of a solar PV system through the inverter. The goal of curtailment is to smoothen the PV power output profile by limiting sudden power changes (dP in Eq. (1)) and subsequently prevent voltage fluctuations.

For the deployment of active power curtailment, the voltage profile in the LV grid is continuously monitored. This is achieved by simulating the power flows in the LV grid through considering the supply and demand at each node. In case the simulated voltage profile results in a voltage fluctuation that exceeds the predefined threshold for ΔV, power is curtailed. Consequently, ΔV is used as a trigger that activates curtailment. Next, as the curtailment of power indirectly affects the voltage profile, the grid simulation requires continuous updating. To this purpose, after each time step at which curtailment is activated, an updated voltage profile is simulated. To limit the computational expenses, the updated profile for each time step is limited to five consecutive iterations, which is deemed sufficiently accurate. To implement this approach successfully, insight into the near future is essential as, for instance, curtailment needs to be applied seconds before the actual drop in the power production is observed. To not complicate the study, a perfect forecast of the PV power output is considered, which can be seen as the theoretical potential of the effectiveness of dynamic curtailment. Besides, advanced PV power forecasting models can be applied to generate these forecasts [38–42].

2.2.2. Grid reinforcement

The second mitigation strategy, grid reinforcement, aims to lower the resistance (R in Eq. (1)) by strengthening the grid capacity. Consequently, this strategy makes the system less vulnerable to abrupt changes in the power output of PV systems (dP). For instance, replacing a GPLK 4 × 25 mm Curm cable, which is commonly found in the LV grid in the Netherlands, with a 4 × 150 mm VVMvKhas/Alk 4 × 6 would reduce the resistance in the cable by approximately 72% and thus reduce the severity of voltage fluctuations.

In this study, grid reinforcement is considered as replacing all current LV cables with their equivalent that dispose over the lowest resistance. For the LV grid this concerns the 4 × 150 mm VVMvKhas/Alk 4 × 6 cable [17]. This particular application is considered because it shows the technical potential of grid reinforcement to mitigate voltage fluctuations. Besides, this strategy is deemed as more feasible compared to redesigning the entire local grid layout of an urban area.

2.2.3. Supercapacitor

Similar to active power curtailment, the supercapacitor aims to limit voltage fluctuations by minimizing abrupt changes in the power output of PV systems. A supercapacitor can temporarily store electricity such that power can be fed to the grid with some delay. By storing power seconds before or during a ramp event, it has the ability to smoothen the PV power output profile, minimize dP and subsequently limit ΔV. A great advantage of a supercapacitor over other mitigation strategies is its easy placement throughout the grid. However, similar to active power curtailment, a perfect forecast of the expected power changes is required to maximize its effectiveness. Alternatively, a supercapacitor that is always slightly (e.g. 50%) charged to accommodate power changes in both directions is needed. However, this will increase the required capacity and thus the costs of the supercapacitor. To evaluate the technical potential of the supercapacitor, a perfect forecast of active power is assumed.

The capacity of a supercapacitor can be quantified according to Eq. (2). Here, E denotes the capacity of the supercapacitor in [Wh], C equals the capacitance of the supercapacitor in Farads [F] and V is the operating voltage. Eq. (2) shows that the capacity of a supercapacitor is determined by both its capacitance and operating voltage. For a supercapacitor to be able to mitigate voltage fluctuations caused by solar PV, its capacity should be capable to store sufficient electricity for a specific time period. Additionally, the charging and discharging power capacity must suffice to accommodate the required ramp rates to smoothen the power output of a PV system.

$$E = \frac{1}{2}CV^2. \tag{2}$$

To assess the technical potential of supercapacitors to prevent voltage fluctuations in the LV grid, it is assumed that a supercapacitor is placed at every PV system. By placing the supercapacitor between the solar PV panels and the inverter, unnecessary AC/DC and DC/AC conversion losses are avoided as both the PV system and supercapacitor operate in DC. The operation of a supercapacitor is in this study mimicked by applying a moving average to the solar PV profile, see Eq. (3). Here, T presents the period over which electricity is stored in seconds.

$$P_{t,T} = \frac{1}{T}\sum_{t=-\frac{1}{2}T}^{\frac{1}{2}T} P_t. \tag{3}$$

A supercapacitor is deemed to be able to provide a power output profile as generated by the moving average algorithm when its size and charge/discharge capacity is sufficient [43,44]. The optimal size (SC_{size}) and capacity (SC_{cap}) of the supercapacitor are determined based on the requirements set by the moving average algorithm. These requirements are determined by first subtracting the initial solar PV profile (P_i) from the smoothed solar PV profile (P_s). The required charge/discharge capacity equals the maximum difference between P_i and P_s observed (see Eq. (4)). Furthermore, the size of the system is equal to the difference between the maximum and minimum charge of the supercapacitor, which is determined by Eq. (5). Since the size of the supercapacitor highly depends on the period over which it is expected to charge/discharge and store electricity, three different types of supercapacitors are evaluated that adopt a moving average window of T is 6, 10 and 20 seconds respectively.

$$SC_{cap} = max(|P_{i,t} - P_{s,t}|). \tag{4}$$

$$SC_{size} = max(|\int_0^T (P_{s,t} - P_{i,t})dt|). \tag{5}$$

Finally, the supercapacitor experiences power losses due to charging and discharging as well as DC/DC conversion. Since the efficiencies of these processes depend on numerous factors, including the resistance within the capacitor, operating voltage, frequency, temperature, current and size [45], its values are not constant over time. This issue is further discussed in Section 4.4.1.

2.3. Grid simulations

The modeling software DIgSILENT PowerFactory 2019 SP2 is used to simulate the voltage levels in the LV grid [46]. The DIgSILENT PowerFactory software considers a quasi-dynamic load-flow simulation and is widely used in power system and load flow analysis [29]. Due to uncertainty on existing and future connections of PV systems and households, in these simulations a perfect balance among the three-phase cables is assumed. Furthermore, it is assumed that the MV grid, connected to the analyzed LV grid, does not cause additional voltage fluctuations. This assumption is made due to the absence of MV grid data, computational barriers to simulate the MV grid and the uncertainty on how the effect of the MV grid on the distribution grid will change with an increasing installed solar PV capacity. The results in this study are obtained through grid experiments for August 4, 2017. The assessment is for computational reasons limited to one day. Besides, this study aims to examine the technical potential of the voltage regulation techniques. Therefore, the adopted strategy should be able to withstand all levels of observed voltage fluctuations including the most extreme fluctuations, which are for 2017 observed at August 4 (see Section 3.4). Since the demand is not found to cause problematic fluctuations in Section 4.1, the experiments are limited to PV production hours only, i.e. from sunrise to sunset. Finally, in this study the voltage levels are monitored at the transformer station as well as 11 nodes distributed throughout the LV grid.

3. System design

In this section the inputs needed for the experiments are described. First, it discusses the grid characteristics of the studied area and the scenarios for PV growth. Thereafter, the electricity demand and PV production profiles are presented.

3.1. Grid characteristics

The impact of an increasing number of distributed PV systems on voltage fluctuations in the LV grid as well as the potential of the identified regulation strategies are examined on an existing LV grid in Lombok. Lombok is a relatively densely populated urban area located in Utrecht, the Netherlands [47]. For the simulations in this study, a digital twin of the local LV grid is made considering the number of connections, cable lengths, and the corresponding equipment and resistances. Via 11 main LV cables, 13 sub-cables and 8 distribution substations, the grid connects a total of 343 grid points through a MV/LV transformer station to the MV grid. In total, 91% of the length of the cables in the system concern GPLK cables [29], and the remainder are VVMvKhas/Alk 4 × 6.

3.2. Scenarios

As discussed in Section 1, a rapid growth of distributed PV systems is expected in the next decade. To be able to identify the impact of an increasing solar PV capacity in the LV grid and assess the potential of the voltage regulation strategies presented above, this paper studies three scenarios of PV growth. In these scenarios the PV penetration rate is expected to grow from an estimated 6% today to 40, 70 and 100% of the available rooftop capacity. Here, the rooftop capacity is defined as those residences that have the technical ability to place a solar PV systems, which is 215 out of the 343 grid connections. A 100% PV penetration scenario therefore implies that a PV system is installed at 215 grid connections. The expected capacity of each of these systems is set randomly, by picking a value from a generated data set considering a normal distribution with a mean of 3.6 kWp and a standard deviation of 1.0 kWp. These values are chosen since they can be considered as typical for rooftop PV systems in the Netherlands [42,48]. Moreover, the observed installed capacities originate from a net-metering policy that is in place in the Netherlands. This policy stimulates residents to install a PV system that on a yearly basis generates an electricity volume that is equal to their demand. Therefore, in the 100% scenario, sufficient electricity is produced to meet the annual demand of 215 out of 343 residences. As a result, in this scenario a self-sufficiency rate of 63% is reached. In conclusion, the 40%, 70% and 100% PV penetration rate, respectively, equate to an installed capacity of 310, 542 and 774 kWp in the studied LV grid.

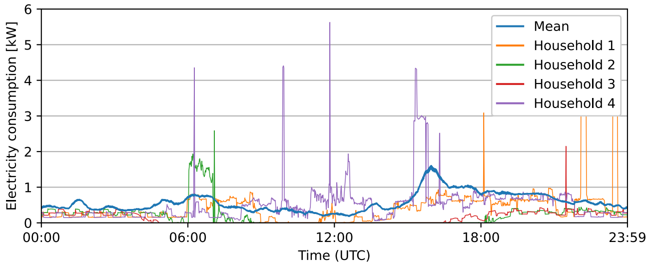


Fig. 1. The mean electricity demand for all 343 connected households along with the individual demand profile of four randomly selected households, i.e. at four grid nodes.

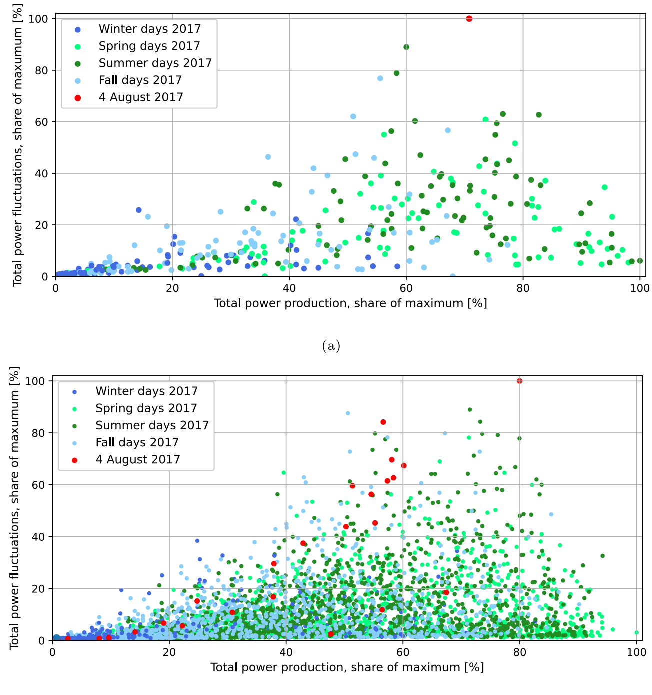
3.3. Demand profiles

Although 20 grid connections are identified as shops and schools, for simplicity reasons all 343 grid connections are considered to be households. These household demand profiles are composed based on one-minute data of five individual households over a period of one week. Since the experiments in this study are executed with a two-second resolution, first two-second demand data is constructed through linear interpolation of the original one-minute measurements. Subsequently, by means of shifting the demand profiles in time, 343 individual demand profiles are created. Fig. 1 shows the generated electricity demand profile for four random households as well as the mean demand profile for all connected households.

3.4. Solar PV profiles

In addition to the demand profiles, each grid connection requires a unique PV power output profile. This is essential as transient clouds block the solar irradiance on nearby located PV arrays a few moments apart, depending on wind speed and direction. This study considers the PV power output profile of four PV systems that have been monitored in the Lombok area on a two-second resolution [42]. All other PV power profiles are generated by considering inverse distance weighted interpolation. Such method has been applied to estimate the PV power output profile in other studies, albeit for other temporal and spatial resolutions [49,50]. A disadvantage of this interpolation method is that the generated PV power output profiles become more smooth compared to the actual measured profiles. Results show that in the most extreme case, a decrease of the observed ramp rate of 11% is found due to inverse distance weighted interpolation. However, alternative methods, such as kriging [50–52], were deemed unreliable when fed by only four systems [53].

In order to interpret the results from the grid simulation on August 4, 2017 and determine what can be expected at other days throughout the year, the observed fluctuations in the PV power output is in Fig. 2 compared for the entire year. Moreover, in Fig. 2(a) the x-axis presents the relative electricity production for each day ($\sum E$) with respect to the day with the most PV power production ($\sum E_{max}$). The y-axis in Fig. 2(a) depicts the relative power fluctuations by presenting the sum of the observed daily power fluctuations for each day in 2017 $\sum |P_i - P_{(i-1)}|$ to the maximum value observed in 2017 $\sum |P_i - P_{(i-1)}|_{max}$. Similarly, Fig. 2(b) shows this relation per 30 min. From Fig. 2(a), it can be found that for 2017 most fluctuations in



(a)

(b)

Fig. 2. The figure shows a scatterplot considering the observed variability to the summed power output of an individual PV system. Plot (a) indicates these variations per day, whereas plot (b) presents them per interval of 30 min for the indicated days.

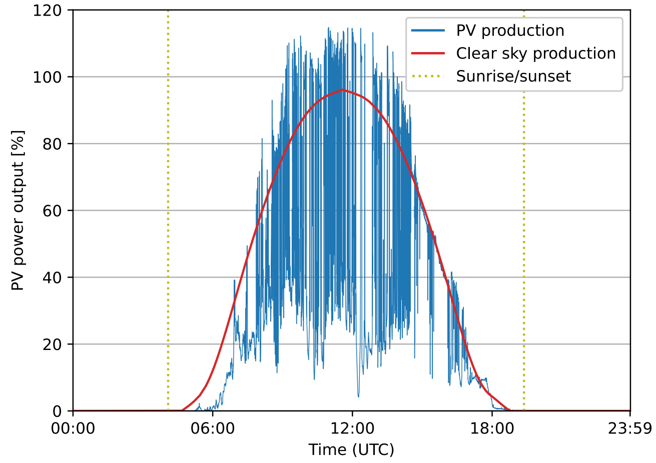


Fig. 3. The normalized power output of a single PV system on August 4, 2017.

the power output are experienced at August 4. Although to a lesser extent, several other days in spring and summer approach the amount of fluctuations experienced at this day. Additionally, from Fig. 2(b), it can be seen that throughout the year there are many other shorter periods (of 30 min) that encounter similar fluctuations as on August 4. This demonstrates that these levels of ramp rates are not restricted to one day. Since the aim of this study is to assess the technical potential of the voltage regulation techniques to prevent or mitigate the most extreme observed fluctuations throughout the year, all experiments are run for August 4. An example of the power production profile of a single PV system on this day can be found in Fig. 3. In addition, this figure shows the expected power output of the same PV system at this day in case of clear sky conditions.

Table 1

Results on the amount of time the observed voltage fluctuations at each LV grid point exceed the visible ($0.83\Delta V/2s$) and irritating ($1.92\Delta V/2s$) threshold per scenario.

Scenario	Visible fluctuations [%]			Irritating fluctuations [%]		
	40%	70%	100%	40%	70%	100%
Node 1	0.09	1.38	3.47	0	0.01	0.14
Node 2	0.10	1.53	3.80	0	0.01	0.17
Node 3	0.46	2.77	5.44	0	0.16	0.65
Node 4	0.84	3.93	7.06	0	0.30	1.10
Node 5	0.69	3.26	5.97	0	0.21	0.79
Node 6	0.96	4.26	7.37	0	0.37	1.27
Node 7	0.30	1.71	3.48	0	0	0.09
Node 8	0.67	2.36	4.31	0	0.01	0.19
Node 9	0.75	2.67	4.64	0	0.02	0.23
Node 10	0.21	1.84	3.92	0	0.03	0.29
Node 11	0.74	2.66	4.62	0	0.01	0.22
Transformer	0	0.04	0.24	0	0	0

4. Results

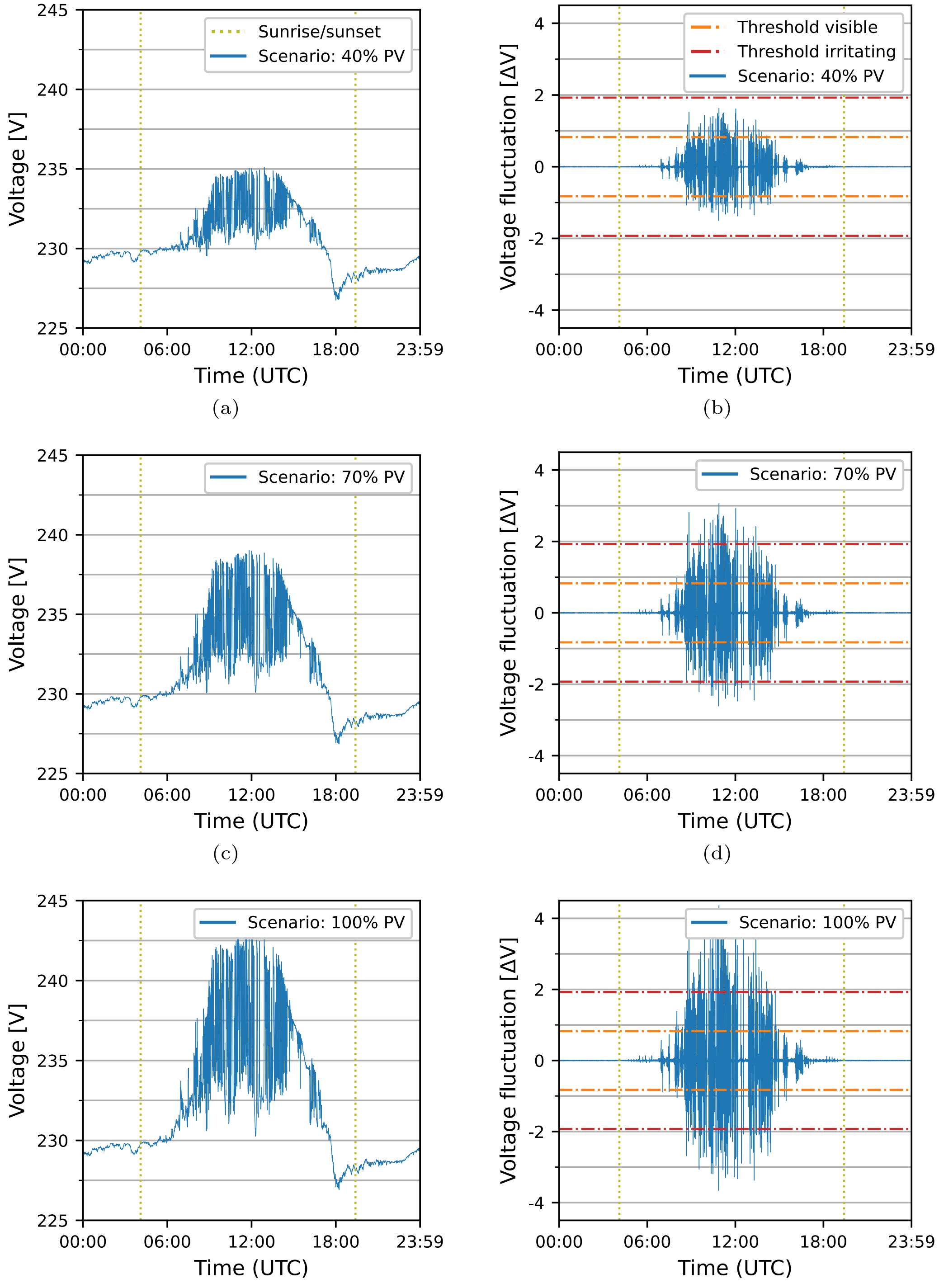
In this section, first the impact of the power output of PV systems on the voltage profile and corresponding fluctuations in the LV grid is presented per scenario. Next, the technical potential of the mitigation strategies to prevent or limit problematic voltage fluctuations is examined. Finally, the effectiveness of the mitigation strategies is compared amongst each other.

4.1. Without interference

This section presents the impact of distributed PV power generation on the voltage levels observed in the Lombok LV grid for the current situation as well as the three scenarios. Table 1 presents the frequency in which the thresholds related to acceptable voltage fluctuations is exceeded at different nodes in the LV grid and at the transformer station. Firstly, Table 1 clearly depicts the extent of the problem related to voltage fluctuations caused by PV systems. This is substantiated as from a 40% penetration level, all nodes in the LV grid experience visible quality problems. For example at node 3, during 0.5% of time visible related problems are observed in the 40% PV scenario, increasing to 5.5% of time for the 100% scenario. Furthermore, the second threshold, which is related to irritating quality problems, is violated from a penetration level of 70%. At node 4 these irritating fluctuations occur 0.3% of time in the 70% PV scenario and increase up to 1.1% of time in the 100% scenario. Another effect that can be observed in Table 1 is the varying degree of the observed voltage fluctuations per node. For example, the frequency at which problematic fluctuations are encountered at node 6 are significantly higher for all scenarios compared to node 1. Since the aim of this study is to evaluate the competence of the mitigation strategies in dealing with voltage fluctuations, unless otherwise stated, the remainder of this study will focus on the fluctuations experienced at node 6.

Fig. 4 depicts per scenario the voltage profiles observed in the LV grid, as well as the voltage fluctuations that correspond to these profiles. From the plots in Fig. 4, it becomes clear that the observed voltage fluctuations can be attributed to changes in the PV power output as the fluctuations before sunrise and after sunset are minimal. Moreover, the most significant fluctuations in the voltage profile are observed around midday, where in absolute terms the potential change in the power output can be most extreme. Furthermore, Fig. 4 shows that the voltage fluctuations become more extensive as the PV penetration rate in the LV grid grows. This is substantiated as with a larger PV power output, which comes with a growing number of connected systems, the stress on the LV grid increases. Finally, the voltage level is in any scenario observed to remain between 227 and 243 V, which lay well within the 10% variation thresholds that is allowed for in the LV grid.

For each scenario, Fig. 5 presents the frequency of occurrence of voltage fluctuations with decreasing severity. Additionally, the plot



(a) (b)

(c) (d)

(e) (f)

Fig. 4. Figure indicating the observed voltage profiles (a), (c) and (e), and voltage fluctuations (b), (d) and (f) on August 4, for PV penetration scenarios of 40%, 70% and 100%, respectively.

indicates the thresholds discussed in Section 2.1.1. The results show that in each scenario the visible threshold is exceeded for numerous two-second time steps. Moreover, from Fig. 5 it can be observed that the irritating threshold is exceeded for multiple time steps in the 70% and 100% scenarios. When considering the 40% scenario, a maximum voltage fluctuation of 1.6 ΔV/2s is observed. Moreover, the visible threshold is exceeded during 1.0% of all time steps. For the 70% PV scenario, a maximum voltage fluctuation of 3.1 ΔV/2s is found, which almost doubles the findings for the 40% scenario. Subsequently, the irritating threshold is crossed 0.4% of the time, whereas the visible threshold is exceeded 4.3% of the time. Finally, in the 100% scenario a maximum voltage fluctuation of 4.4 ΔV/2s is experienced, which is more than twice as high as the limit set by the irritating threshold. In this scenario, the caused voltage fluctuations are classified as visible and irritating in respectively 7.4% and 1.3% of the time. Consequently, Fig. 5 elucidates an increase in power quality problems that can be expected in any LV grid as a direct result of a growing PV penetration rate.

Table 2
The occurrence of problematic voltage fluctuations and the power losses when active power curtailment is applied.

PV penetration level	Cumulative curtailed [%]	Visible fluctuations [%]		Irritating fluctuations [%]	
		No curtailment	Curtailed	No curtailment	Curtailed
40%	0.51	0.96	0.01	0	0.01
70%	1.45	4.26	0.33	0.37	0.04
100%	2.26	7.37	1.01	1.27	0.10

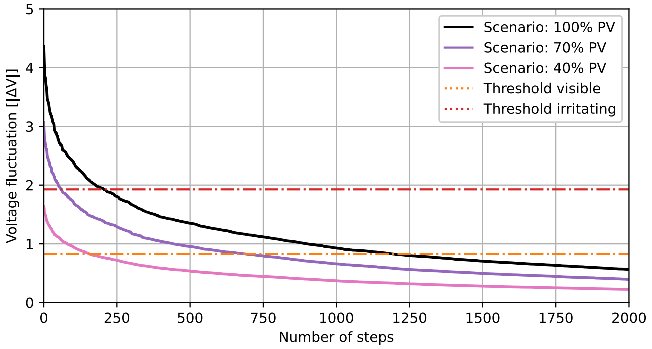


Fig. 5. The 2000 largest observed voltage fluctuations per two-second time step for each PV penetration scenario on August 4, 2017 as well as the classified thresholds.

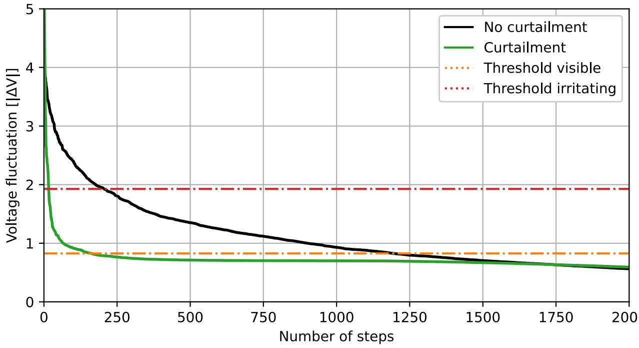


Fig. 6. The 2000 largest observed voltage fluctuations in the LV grid before and after introduction of active power curtailment per two-second time step for the 100% scenario, for five iterations.

4.2. Active power curtailment

The first strategy that is examined on its effectiveness to prevent voltage fluctuations is active power curtailment. Table 2 summarizes the results for this strategy per scenario. For example, Table 2 indicates that in the 100% scenario the occurrence of visible fluctuations is decreased from 7.4% to 1.0% of time. However, these results show that in each scenario, both visible and irritating voltage fluctuations are still experienced. The simulation results in Table 2 show that curtailment was able to mitigate at least 86% of the problematic voltage fluctuations in all scenarios. Next, the 2000 time steps that experience the most intense voltage fluctuations in case of the 100% scenario are depicted in Fig. 6. Fig. 6 clearly visualizes that the implementation of this strategy results in less severe voltage fluctuations, reducing the occurrence of problematic fluctuations significantly.

Furthermore, from Table 2 it is intriguing that problematic fluctuations are observed in all simulations as for the 40% scenario no irritating fluctuations are found in case active power curtailment is not applied. Similarly, the maximum encountered voltage fluctuation is found to increase in all scenarios. This is a direct consequence of the voltage mitigation strategy applied, which is based on the simulated voltage profile, and how this mitigation strategy is implemented in this study, where the number of iterations is limited to five. Moreover, after a single iteration in which a problematic voltage fluctuation is dealt with, a new problematic voltage fluctuation may occur due to a potential shift of the ramp rate in time. Based on the results, it is expected that no problematic fluctuations would occur if sufficient resources are available to simulate a large amount of iterations. However, this would then raise the question whether these computational necessities can be met in real-time.

All together, these results show that active power curtailment has significant potential to mitigate voltage fluctuations. In addition, Table 2 shows the amount of cumulatively curtailed power from the solar PV systems. The maximum observed power curtailment is found in the 100% scenario and amounts to 2.3% of the total daily power output of all solar PV systems connected to the LV grid. Consequently, active power curtailment is found to achieve significant reductions in the voltage fluctuations at a cost of relatively little power losses.

4.3. Grid reinforcement

Table 3 holds the results for the second examined strategy, i.e. grid reinforcement. The results show that by means of grid reinforcement a substantial part of the voltage fluctuations in each scenario is mitigated. For example, Table 3 shows that grid reinforcement has the potential to decrease the occurrence of visible fluctuations from 7.4% to 3.9% of time in the 100% PV scenario. However, the extent to which grid reinforcement can mitigate the experienced voltage fluctuations is insufficient, especially as the PV penetration increases. Moreover, less than half of the fluctuations that cause visible fluctuations was mitigated in the 100% PV scenario.

The effect that grid reinforcement has on the observed voltage fluctuations is clearly visible in Fig. 7. The construction of new LV cables leads to a relatively even reduction in the magnitude of the voltage fluctuations, but does not prevent its occurrence. Consequently, grid reinforcement may be observed as a temporary solution that holds up until a certain level of connected distributed PV systems has been reached. Given these results, it can be concluded that the proposed grid reinforcement strategy, which includes replacing all LV cables by their most advanced counterparts in terms of capacity, is insufficient when the PV penetration rate grows beyond 40%.

4.4. Supercapacitor

The impact of adopting a supercapacitor at each PV system on the observed voltage fluctuations is for each scenario presented in Table 4. It shows the results for three different types of supercapacitors, obtained through considering 6, 10 and 20 seconds moving average window (see Section 2.2.3). The results show that a 6-second moving average window is almost sufficient to mitigate all fluctuations in case of a PV penetration rate of 40%. Nevertheless, as the PV penetration rate grows to 70% only the supercapacitor that considers a 20-second moving average proves to be sufficient. Moreover, the visible threshold is only exceeded in 0.1% of time for the 20-second moving average solution. As a result, from Table 4 the conclusion can be drawn that the larger the period over which the power output can be fed into the

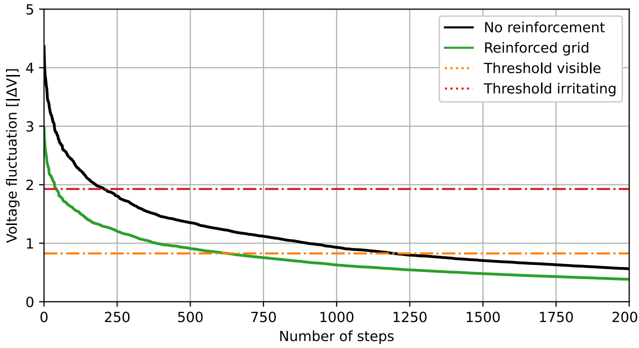


Fig. 7. The 2000 largest observed voltage fluctuations in the LV grid before and after grid reinforcement for the three scenarios.

Table 3
The occurrence of problematic voltage fluctuations before and after reinforcing the local LV grid.

PV penetration level	Visible fluctuations [%]		Irritating fluctuations [%]	
	Not reinforced	Reinforced	Not reinforced	Reinforced
40%	0.96	0.21	0	0
70%	4.26	1.78	0.37	0.02
100%	7.37	3.86	1.27	0.26

grid, the higher the potential of a supercapacitor to mitigate voltage fluctuations.

Similar results can be observed from Fig. 8, which holds the 2000 most intense voltage fluctuations experienced per supercapacitor. These results show the superiority of a supercapacitor that is able to smoothen the PV power output over a 20-second period. In conclusion, the supercapacitor proves to be a suitable technology for mitigating voltage fluctuations if its characteristics suffice the identified needs.

4.4.1. *Characteristics of the supercapacitor*

The characteristics of available supercapacitors vary, and therefore the type of capacitor that is needed depends directly on the maximum charging/discharging power needed and the volume of its capacity. This study has gathered the requirements in terms of storage and power for each of the three simulated supercapacitors, i.e. 6, 10 and 20 seconds. The requirements are summarized in Table 5. The results show that a larger size and ramp rate is required as the operation period of the supercapacitor increases.

Lastly, although no AC/DC conversion or vice versa is needed, efficiency losses still occur during storage by a supercapacitor and possibly during DC/DC conversion. Supercapacitors are found to have efficiencies of over 98%, whereas in ideal circumstances, supercapacitors can reach an efficiency of close to 100% [45].

4.5. *Comparison of mitigation strategies*

4.5.1. *Technical comparison*

Fig. 9 displays the voltage fluctuations that are experienced in the LV grid during an hour in case of a 100% PV penetration level. The plots show the results for each mitigation strategy and in case no action is taken to mitigate or prevent voltage fluctuations. Besides, the thresholds that mark problematic fluctuations are shown. Fig. 9(a) shows the high frequency of problematic voltage fluctuations that can be expected during a single hour in case no mitigation strategy is deployed. The effect of reinforcing the LV grid on the observed voltage fluctuations can be examined by comparing Figs. 9(c) to 9(a). These plots show the close resemblance between the observed voltage fluctuations, whereas grid reinforcement will succeed in reducing the magnitude of voltage fluctuations while not preventing for fluctuations.

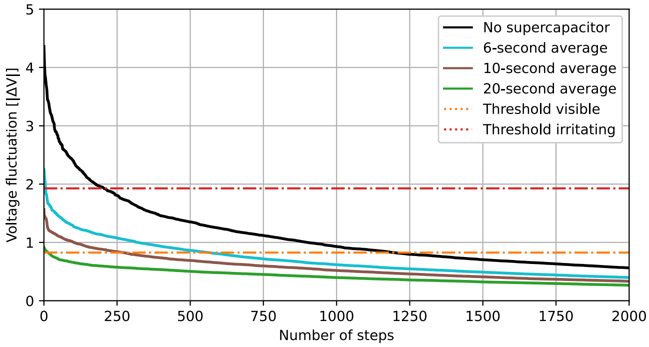


Fig. 8. The 2000 largest observed voltage fluctuations in the LV grid before and after installing a supercapacitor at all PV systems for the three scenarios.

Table 4
The occurrence of problematic voltage fluctuations before and after installing a supercapacitor at all PV systems in the local LV grid.

PV penetration level	Visible fluctuations [%]				Irritating fluctuations [%]			
	Without	6-s	10-s	20-s	Without	6-s	10-s	20-s
40%	0.96	0.02	0	0	0	0	0	0
70%	4.26	1.06	0.19	0	0.37	0	0	0
100%	7.37	3.48	1.66	0.09	1.27	0.04	0	0

Table 5
Specified requirements for a supercapacitor when considering a 100% PV penetration scenario, values reported to the installed PV capacity.

Time window	Size [Wh/kWp]	Ramp rate [kW/kWp]
6-s	1.04	0.87
10-s	1.24	1.23
20-s	1.38	1.50

Consequently, although grid reinforcement succeeds in limiting voltage fluctuations throughout the depicted hour, problematic fluctuations are still frequent.

Fig. 9(b) shows the voltage fluctuations in the LV grid when active power curtailment is deployed to prevent problematic voltage fluctuations. The results show that by means of curtailment, the magnitude of voltage fluctuations is mostly kept within the visible threshold. This is because power was only curtailed when a fluctuation exceeds 0.7 $\Delta V/2s$. However, this appears to come at a cost of few very high fluctuations that greatly exceed the irritating threshold, which is previously identified as a direct result of the adopted methods to simulate active power curtailment and may be disregarded (see Section 4.2). By comparing these results to a situation without interference (Fig. 9(a)) or in case of grid reinforcement (Fig. 9(c)), the deployment of curtailment leads to a reduction in the magnitude of and less problematic fluctuations (see Tables 2 and 3).

Finally, the effect of installing supercapacitors on the observed voltage fluctuations can be examined by comparing Figs. 9(d) to 9(a). In Fig. 9(d) no problematic fluctuations are observed when this mitigation strategy is considered. Besides, the relative stable voltage fluctuation profile depicted in Fig. 9(d) is outstanding compared to the other fluctuation profiles (Figs. 9(a), 9(b) and 9(c)). Consequently, from a technical perspective the supercapacitor is clearly found to deal with the voltage fluctuations most effectively.

4.5.2. *Qualitative comparison*

Furthermore, Table 6 presents an overview of the main requirements and accessory consequences for successful implementation of each voltage regulation strategy. Firstly, the adoption of some of the voltage regulation techniques result in electricity losses. Moreover, in case of active power curtailment, electricity is lost as the power production of PV systems is reduced during times of curtailment. However,

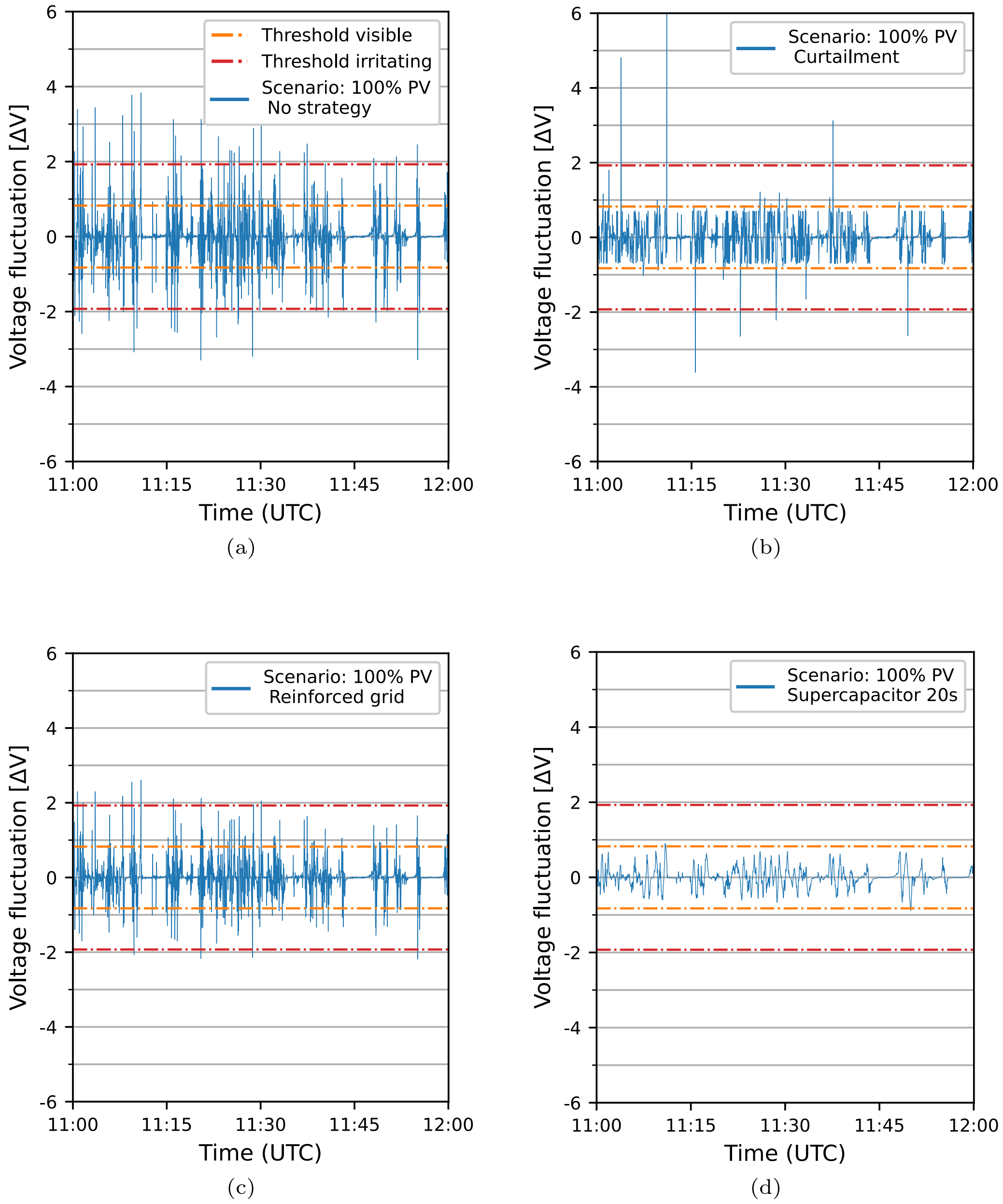


Fig. 9. Profiles of voltage fluctuations observed in the LV grid between 11:00 and 12:00 in case of (a) no intervention, (b) active power curtailment, (c) grid reinforcement, and (d) supercapacitor.

this only applies when curtailment is activated. The implementation of supercapacitors will result in electricity losses at all times, due to the efficiency losses caused by storing electricity and DC/DC conversion. Grid reinforcement does not cause additional electricity losses.

Secondly, some additional technical requirements are necessary in case of active power curtailment. The successful implementation of this strategy requires continuous processing of the power flows per node, and subsequently, grid simulations. Besides, curtailment requires accurate forecasts of the PV power output. Such a forecasting algorithm is also needed for supercapacitors in order to limit the storage capacity, see Section 2.2.3. Grid reinforcement does not demand additional technical requirements to support operation after the construction phase.

Finally, Table 6 summarizes the economic implications related to the implementation of each technique. Moreover, grid reinforcement requires relative high investments related to the replacement of existing LV cables [21]. Similarly, in case of supercapacitors, investments related to the installation of a supercapacitor per PV system should be considered. For the third option, active power curtailment, the costs depend on the current situation of the grid infrastructure. Moreover, if not present already, a smart metering system should be installed per node. In addition, operational costs are to be made to enable continuous data processing and grid simulations.

4.5.3. *Overall comparison*

Overall, supercapacitors are preferred over grid reinforcement and active power curtailment to regulate the voltage level and prevent problematic voltage fluctuations. Furthermore, from a technical perspective the adoption of supercapacitors outperform grid reinforcement as the latter strategy is not able to mitigate problematic voltage fluctuations, especially not when the PV penetration rate in the LV grid exceeds 40% (see Section 4.3). Next, from a practical perspective, including the implementation and operation of the voltage regulation techniques, supercapacitors are preferred over active power curtailment due to the accessory technical needs related to successful implementation of curtailment.

Table 6
Overview of the qualitative requirements and accessory consequences of successful implementation for each voltage regulation technique.

Regulation technique	Requirements for successful implementation	Consequences of adoption
Active power curtailment	1. A smart metering system per grid node, which can communicate electricity production and consumption values. 2. Accurate short term (<20 s) forecast of PV power output.	**Electricity losses** 1. During curtailment, electricity production from PV systems is lost. This is up to 2.3% of the expected electricity production at highly variable days.
		Technical 1. The voltage levels must be monitored continuously throughout the entire LV grid. 2. Production and consumption data must be available to monitor grid voltage levels. 3. An operational algorithm that forecasts the PV power output is needed.
		Economic 1. Possibly, costs associated with installing a smart metering system. 2. Possibly, costs associated with placement of smart inverters. 3. Costs associated with running back-end, server hosting data collection and grid simulations.
Grid reinforcement	1. Replacement of all LV grid cables.	**Electricity losses** No additional electricity losses.
		Technical No technical requirements needed to support operation.
		Economic 1. High costs associated with replacement of LV cables.
Supercapacitor	1. Installation of a supercapacitor per PV system. 2. Possibly, accurate short-term (<20 s) forecast of PV power output.	**Electricity losses** 1. Electricity losses at all times. This is around 2% of the total electricity production, assuming a supercapacitor with a round trip efficiency of 98%.
		Technical 1. Operational algorithm that forecasts the PV power output is needed.
		Economic 1. Costs associated to installing a supercapacitor at all PV systems.

5. Conclusions

This study investigated the potential of three voltage regulation strategies to prevent or mitigate problematic voltage fluctuations in the LV grid, which are caused by rapid changes in the power output of distributed PV systems. To this end, first the magnitude and frequency of (problematic) voltage fluctuations are assessed for three scenarios of PV growth, which correspond to a PV penetration rate of 40%, 70% and 100% in the studied district. Next, the potential of active power curtailment, grid reinforcement and the deployment of supercapacitors to mitigate the problematic voltage fluctuations in each scenario are examined. In this study, all experiments are run for an urban LV grid located in Utrecht, the Netherlands, using high resolution data for a single exemplary day that experiences high fluctuations in the PV power output.

The results show an increasing number and magnitude of voltage fluctuations in the LV grid in accordance with a growing amount of PV systems. Although no problematic fluctuations are observed in the current situation, voltage fluctuations that exceed the visible threshold are found for all growth scenarios. More specifically, the frequency of occurrence of these kind of voltage fluctuations increases up to 7.4% for the 100% PV growth scenario. Besides, for the 70% and 100% growth scenarios, voltage fluctuations are found to exceed the irritating threshold in 0.4% and 1.3% of time, respectively. As a result, an increasing number of distributed PV systems will lead to problematic voltage fluctuations in the LV grid.

All three regulation techniques are found to be able to lower the magnitude of voltage fluctuations and therewith limit the number of problematic fluctuations. From the results it can be concluded that the supercapacitor is preferred over the alternative voltage regulation strategies considering the number of observed problematic fluctuations. Besides, the smoothed PV power output profile due to the supercapacitor greatly reduces the number and magnitude of all voltage fluctuations. In addition, active power curtailment proves to be a descent alternative as it succeeds in limiting the number of problematic voltage fluctuations to a respectable amount. However, in order to enable successful implementation, multiple operational demands must be met. Grid reinforcement does not prove an adequate alternative since the observed reduction in fluctuations is relatively limited, especially as the PV penetration rate grows. Overall, this paper identifies the supercapacitor, which has the capability to distribute the PV power output over a 20-second period, as the best option to mitigate voltage fluctuations.

In light of this study, future work should focus on examining the potential of the suggested mitigation strategies in other case studies, e.g. in more rural parts of the LV grid. Besides, the potential of an alternative mitigation strategy, where few supercapacitors are adopted in the LV grid instead of a situation in which every PV system is equipped with a supercapacitor should be investigated. For instance, placing larger supercapacitors at strategic locations throughout the grid may qualify as an interesting alternative. Finally, future studies should aim to quantify costs and benefits associated with each voltage mitigation strategy in an economic assessment.

CRediT authorship contribution statement

L.R. Visser: Conceptualization, Data curation, Methodology, Writing – original draft, Writing revisions. **E.M.B. Schuurmans:** Conceptualization, Data curation, Methodology, Software. **T.A. AlSkaif:**

Writing – review & editing, Supervision. **H.A. Fidder:** Conceptualization, Supervision. **A.M. van Voorden:** Conceptualization, Supervision. **W.G.J.H.M. van Sark:** Writing – review & editing, Supervision.

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.

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