28-05-2020

The Effect of Solar PV on Voltage Flicker in the LV Grid

Identifying the magnitude of the voltage flicker problem with an increasing installed solar PV capacity and assessing the potential for voltage flicker mitigation using different voltage regulating techniques

Schuurmans, EMB (Erik)
STUDENT NUMER: 4101227
E.M.B.SCHUURMANS@STUDENTS.UU.NL
MSC THESIS ENERGY SCIENCE – 30 ECTS

Supervisors
LENNARD VISSER (UTRECHT UNIVERSITY)
WILFRIED VAN SARK (UTRECHT UNIVERSITY)
ARJAN VAN VOORDEN (STEDIN DSO)
HENK FIDDER (STEDIN DSO

STEDIN.NET

Utrecht University

List of Figures

List of Tables

Acknowledgements

Prior to this thesis, I decided to challenge myself to come up with my own thesis topic, this allowed me to dive deeper into the field of electrical engineering. I have been very interested in this field for a while, but I did not yet have the opportunity to pursue this interest. Naturally, pursuing an unknown field resulted in many challenges that emerged during this thesis. In order to overcome these challenges, I was assisted by many people who I would like to thank.

Firstly, I would like to thank Lennard Visser (Utrecht University) for his elaborate feedback and many insightful discussions about the direction and content of this thesis, as well as for providing me with the solar PV input data. I would also like to thank prof. dr. Wilfried van Sark (Utrecht University) for his feedback. The combined feedback has improved the quality of this thesis.

Secondly, I would like to thank Stedin for providing me with a Laptop capable of processing the almost half a terabyte worth of data and providing me with the software licenses required for this thesis. I would furthermore like to thank Arjan van Voorden (Stedin) and Henk Fidder (Stedin) for making me feel welcome at Stedin, for giving me many technical insights and for the interesting discussions about the direction of this thesis.

Further thanks go to Nico Brinkel (Utrecht University) for helping me out with the PowerFactory software which enabled me to perform my analysis. I would also like to thank dr. ir. Gautham Ram (Delft University of Technology) for his technical insights and validation of the applicability of the voltage regulation techniques used in this thesis.

Lastly, I would like to thank my family, friends and girlfriend for the emotional support during this thesis.

Abstract

Cloud movement can result in a rapidly changing power output of solar photovoltaic (PV) systems. This can result in power quality problems in the distribution network. The larger the installed solar PV capacity, the greater these problems become. Rapidly changing voltage levels in the distribution network result in the power quality related problem of voltage flicker. This thesis aims to quantify the impact of an increasing installed solar PV capacity in the low-voltage (LV) grid on voltage flicker by performing a case study for the Lombok LV grid located in Utrecht, the Netherlands. In order to do so, this thesis uses solar PV data with 2-second resolution and 40%, 70% and 100% PV penetration scenarios. Afterwards, this thesis explores the potential of 1) active power curtailment 2) grid reinforcement and 3) using a supercapacitor for voltage flicker mitigation in each of the scenarios. The results of this thesis show that currently the thresholds of visible (0.826 $V/2s$) and annoying (1.927 $V/2s$) voltage flicker are not crossed in the Lombok LV grid which suggests that there currently is no voltage flicker problem. However, in all of the PV penetration scenarios a significant amount of voltage flicker is present. The larger the PV penetration rate, the more often the thresholds for visible and annoying flicker are crossed. Applying the proposed voltage regulation options to the scenarios shows that active power curtailment is potentially promising for voltage flicker mitigation if very precise (forecast) data is available. Most of the voltage flicker was mitigated whilst only curtailing a maximum of 2.26% of the solar PV power output. Grid reinforcement has some mitigating effect, but not enough to solve the voltage flicker problem. The supercapacitor option is found to be most promising for voltage flicker mitigation, mitigating close to 100% of the voltage flicker in each of the scenarios. However, the installation of supercapacitors would require changes in legislation to make them a mandatory component of solar PV systems. Supercapacitors would furthermore increase the pay-back time of solar PV systems by approximately 6% resulting from efficiency losses and associated costs.

Contents

1. Introduction

The installed solar photovoltaic (PV) capacity is rapidly rising because of its decreasing costs, increasing efficiencies and the preference for renewable energy technologies (Fraunhofer ISE, 2019). With 136 TWh, solar PV was the quickest growing renewable electricity generation technology in 2018 globally (IEA, 2019a) and it is predicted that the global installed solar PV capacity will almost triple in the following decade (IEA, 2019b).

Contrary to conventional electricity generators, more than 70% of the installed solar PV capacity is attached to the Low-Voltage (LV) grid (Von Appen et al., 2013; Olowu et al., 2018). Solar PV systems can have power output ramp rates of up to 70% of its rated power output per minute resulting from cloud movement (van Haaren, Morjaria & Fthenakis, 2014). Because of these ramp rates, the rapid increase in installed solar PV capacity can result in problems in the LV grid. These problems include voltage rise and reverse power flow, voltage flicker, unintentional islanding, power fluctuations and problems with maintaining grid frequency (Shivashankar et al., 2016). These voltage related problems cannot only damage the grid, but also appliances and equipment connected to the grid (Wang, Liserre & Blaabjerg, 2013). Flickering light because of voltage flicker can even result in health related problems for people who are exposed to voltage flicker for a longer time (Wilkins, Veitch & Lehman, 2010). Standards have been set to maintain the power quality in the LV grid. Examples of such standards are the NEN-EN 50160 (NEN, 2010) which states that fluctuations in voltage at the household connection in Europe should stay within a ten percent range (Spring et al., 2015) and the IEC 61000-4-15 standard (IEC, 2017) which limits the voltage flicker in the distribution network (Yang & Kratz, 2009). However, because of the rapid increase in installed solar PV capacity, these standards become increasingly hard to meet (De La Parra et al., 2015).

Chaudhary & Rizwan (2018) identified three types of solutions to mitigate voltage fluctuations resulting from an increasing solar PV capacity. The first possible solution is using Electrical Energy Storage (EES) technologies. These technologies can be used to store excess electricity and feed it back to the grid at convenient times. The prevention of peaks and rapid changes in power production result in a limiting effect to the voltage fluctuations. Examples of EES are Batteries, Pumped hydro storage, flywheels, supercapacitors and compressed air energy storage. However, only batteries and supercapacitors have the capacity to react to voltage fluctuations in less than a second (IEC, 2011) and can be placed throughout the LV grid (Argyrou et al., 2018). The disadvantage of EES is that they often require large investment costs (Kim, Suharto & Daim, 2017).

The second proposed solution by Chaudhary & Rizwan (2018) is using reactive power control to limit voltage fluctuations. Voltage fluctuations are dependent on changes in active and reactive power output. Actively changing the reactive power within a system can potentially limit the disrupting effect of fluctuations in active power. This is a very promising solution in the High Voltage (HV) and Middle Voltage (MV) grids which have low resistance over reactance (R/X) ratio's. The lower the R/X ratio, the larger the effect of reactive power on voltage fluctuations (further explained in Section 2.) (van Oirsouw, 2012). However, since the R/X ratio in the Dutch urban LV grid is generally high because of a relatively low resistance because of short and strong cables (van Oirsouw, 2012), changing the reactive power output will only have a minimal effect on the voltage fluctuations. Therefore, this option is not suitable for Dutch urban LV grids.

The final option proposed by Chaudhary & Rizwan (2018) is the curtailment of active power to limit voltage fluctuations. In active power curtailment, the inverter of a PV system can be used to limit its power output (Chaudhary & Rizwan, 2018). This results in lower voltage fluctuations because of lower ramp rates in power output of the systems. A downside of active power curtailment is that the renewable power production by the PV panels will not be maximized (Shivashankar et al., 2016). Furthermore, active power curtailment can also have a negative impact on the inverter lifetime (Yan, Marais & Saha, 2014).

Besides the three options proposed by Chaudhary & Rizwan (2018), reinforcing the LV grid can also reduce voltage fluctuations. A thicker cable for example has a lower resistance and therefore rapid changes in power output will have a smaller effect on the voltage fluctuations (Von Appen et al., 2013).

There have been few studies that compared (some of) these different options. Von Appen et al. (2013) performed an economic assessment of different voltage control strategies in a suburban grid in Germany. They concluded that especially reactive and active power regulation options perform better economically compared to grid reinforcement. However, this research has a more centralized approach and an economic focus, with limited attention to the actual voltage fluctuations. Das et al. (2018) compared the different EES technologies and concluded that supercapacitors and most battery technologies have the potential to be used for voltage regulation. However, this study did not do any measurements and/or modeling to come to this conclusion. Hashemi & Østergaard (2016) performed an elaborate study, comparing methods and suitability of different voltage regulation techniques. They conclude that grid reinforcement is suitable but expensive and that active power curtailment is almost unavoidable in the future but to a large extent determined by the EES capacity present. They furthermore conclude that reactive power control can increase the maximum allowed PV capacity, but that its effectiveness is very much determined by grid characteristics. Lastly, they conclude that batteries can be suitable for voltage regulation, but that a better ICT infrastructure is required to provide efficient and suitable energy storage management in order to be able to regulate voltage. The downside of this study is again that no actual modeling was done to test the applicability to a real LV grid. Furthermore, this study looked at overvoltage from solar PV without considering rapid voltage fluctuations.

Contrary to the aforementioned studies, Brinkel et al. (2020) did look at rapid voltage fluctuations resulting from solar PV. They did this by using 20-second resolution solar PV data and applied this to a part of the LV grid in Utrecht, the Netherlands in the form of a case study. By predicting the amount of installed heat pumps, the amount of electrical vehicles (EVs) and the solar PV capacity in 2030 and 2050, they calculated the voltage flicker present in these scenarios. Afterwards they looked at the voltage flicker mitigation potential of the batteries of the EVs by using them as an EES technology. Brinkel et al. conclude that EVs are very promising in the mitigation of voltage flicker in the LV grid. However, the downside of this study is that only one voltage regulation technique was evaluated. Furthermore, 20-second resolution solar PV data might be a too large resolution to be able to identify the quick drops/rises in solar PV power production resulting from cloud movement.

These studies all conclude that voltage fluctuations from an increasing PV capacity are a problem, but that there are possible solutions of overcome this problem. However, most of these studies do not carry out actual modeling and only one study looks at the expected increasing solar PV capacity in the LV grid. Moreover, the study that did look at an increasing solar PV capacity only assessed one voltage regulation technique. Furthermore, most of the studies mainly look at overvoltage resulting from the increasing PV capacity and not to the problem of voltage flicker resulting from rapid fluctuations in PV output. This research aims to overcome these limitations by performing a case study for the Lombok area (Utrecht, the Netherlands), using high resolution, 2-second PV experimental power data to create a realistic case study for a LV grid with 323 households are connected. This thesis predicts the severity of the voltage flicker problem for different PV penetration rates, and assesses the effect of different voltage fluctuation regulation techniques. This results in the following research question:

> *To what extent will voltage flicker resulting from solar PV in the LV grid be a problem, and how can voltage regulation techniques help to overcome this problem?*

In order to answer this research question, this thesis is split up into three separate steps. The first step is to build a LV grid model and to use this model to assess the current situation regarding voltage fluctuations. The LV grid model describes the Lombok LV grid case study and it considers a unique PV generation profile and electricity demand for each house in this specific location.

Afterwards, the model from the first step is expanded to include three different PV penetration scenarios to assess the impact of an increase in installed PV capacity in the area. In this step, there is no interference to reduce the voltage fluctuations.

In the final step, active power curtailment, EES and grid reinforcement options are included into the model in order to actively reduce the voltage fluctuations. The results from this step show how much potential these options have and whether or not they are attractive options for Distribution System Operators (DSOs) to use in the future.

The results of this research contribute to understanding the potential impact of voltage fluctuations in the LV grid because of an increasing solar PV capacity. This information can be used by DSOs to determine how much voltage regulation capacity should be available in the future. Furthermore, this research provides insights in the mitigating effect that active power curtailment, grid reinforcement and EES can have on voltage fluctuations, which expands the scientific knowledge about voltage fluctuation mitigation techniques. It also provides information to DSOs with possibly interesting options for voltage regulation. The eventual reduction of voltage fluctuations furthermore results in less damage to electrical appliances connected to the LV grid and it might prevent health problems related to voltage flicker.

This thesis is structured as follows. First, it is described how voltage fluctuations occur and how they might be mitigated. Afterwards, the research method discusses the data required to answer the research question, how this data is used and how and why specific software is used to model the LV grid, voltage fluctuations and the proposed solutions. The method furthermore discusses how the model is altered in order to determine the possible impact of the proposed solutions. Afterwards, the results for the current situation and the PV penetration scenarios are presented, followed by the results for the applied voltage regulation techniques. Lastly, the results are discussed and conclusions are drawn.

2. Theory

In order to be able to answer the research question, it is important to understand how voltage fluctuations in the LV grid occur. First, this section aims to generally explain how the LV grid is designed. Afterwards, it is explained how voltage fluctuations in the LV grid occur and what the effect of an increasing solar PV capacity is on these fluctuations. Furthermore, the boundaries for visible and irritating voltage flicker are discussed. These boundaries are used as performance criteria in the grid simulations. Afterwards, the concepts of active power curtailment, grid reinforcement and EES are elaborated upon.

The LV grid carries electricity from mid-voltage (MV)/LV transformers to the end users of the electricity. Generally, about 150 households are connected to one MV/LV transformer, and 25 households per LV cable (Droste-Franke et al., 2012). In the Netherlands, the LV grid generally operates at 230V, and the voltage in the LV grid should always remain in the 10% range, between 207V and 253V to prevent power outages and maintain power quality (Spring et al., 2015).

As described in the introduction, an increase in installed solar PV capacity can increase voltage fluctuations in the LV grid due to rapid changes in the power output (De La Parra et al., 2015). Even if the voltage remains in between the 10% range of 207V and 253V, voltage fluctuations can still cause voltage flicker, which in turn can damage equipment and cause health related problems (Wilkins, Veitch & Lehman, 2010). According to Spring et al. (2013), voltage flicker is very likely to become an increasing problem in the LV grid with an increasing solar PV capacity. These suspicions are also found by Ari & Baghzouz (2011), Mohammadi & Mehraeen (2016) and Wong et al. (2014).

Qual-Tech Engineers, Inc. (2015) defined limits for voltage flicker according to two categories related to visible flicker and irritating flicker. A visual representation of these limits can be seen in Figure 1. The figure shows that the smaller the time step, the smaller the fluctuations have to be in order to be visible and classified as Irritating. For instance, with a two-second time-step, Figure 1 shows that the voltage is allowed to change 0.36% in order for flicker to be visible and 0.84% for the flicker to be classified as irritating. In the Dutch LV grid, this corresponds to 0.83 V/2s for flicker to be visible and 1.92 V/2s for the flicker to be classified as irritating, considering that the nominal voltage at this point would be 230V.

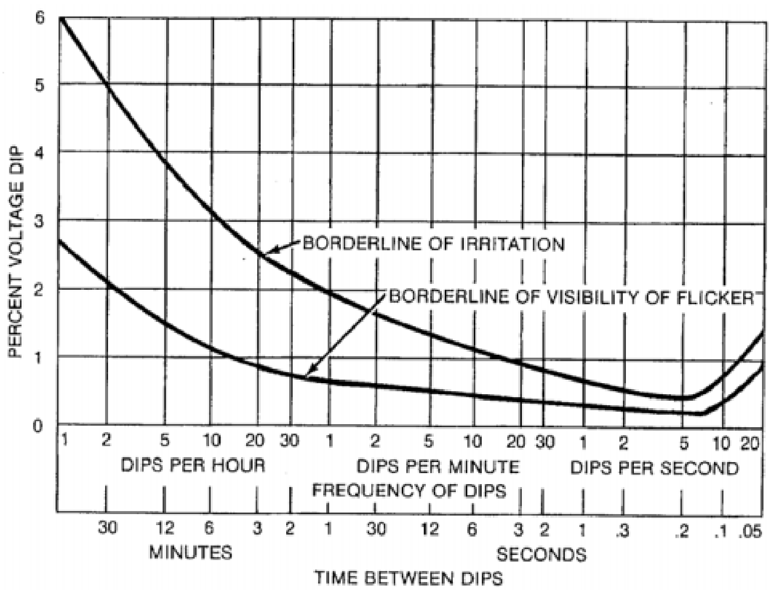

Figure 1: Voltage flicker limits (Qual-Tech Engineers, Inc., 2015)

The changes in voltage along a gird cable resulting from PV can be approximated according to Equation 1 (Chaudhary and Rizwan, 2018).

$$|\Delta V| = \frac{R}{V_R} dP + \frac{X}{V_R} dQ \qquad \text{[Eq. 1]}$$

Equation 1 shows that there are two separate components which affect the voltage fluctuations in a cable. Both components consist of two fixed values and one value which changes over time. The fixed values are the resistance R $[\Omega]$ within the circuit, the receiving end voltage V_R $[V]$ and the impedance X, which is generally expressed in Ohms $[\Omega]$, even though it consists of both real and imaginary values. The changing values over time are the active power P $[W]$ and reactive power Q expressed in volt-ampere reactive $[VAR]$. However, since the R/X ratio in the urban LV grid is generally high (van Oirsouw, 2012), the left part of Equation 1 becomes dominant in the impact on voltage fluctuations. Hence, changing the reactive power output from PV systems will only have a minimal effect on the voltage fluctuations in the LV grid. Therefore, this thesis only includes voltage regulation techniques which actively change parts of the left part of Equation 1. As discussed, these are active power curtailment, grid reinforcement and EES.

Active power curtailment aims to limit $|\Delta V|$ in [Eq. 1] by limiting the active power dP from a solar PV system by using the inverter of the system. Active power curtailment allows full power production until a certain threshold. When this threshold is exceeded, the active power is actively curtailed to limit the possibility of large ramp rates in power production. There are different curtailment strategies, but they can be divided into two categories; static and dynamic active power curtailment (Hashemi & Østergaard, 2016). Static curtailment curtails power based on a pre-defined fixed threshold. An advantage of such a method is that it is relatively easy to incorporate and it does not require much data processing to enable. The major disadvantage of this type of method is that it is less effective and more power is curtailed than in the dynamic method. The dynamic method curtails power based on the voltage levels in the system, which change continuously. This method is more effective and results in less active power curtailed. The disadvantage is that real time measurements and data processing are required (Hashemi & Østergaard, 2016). This thesis uses a dynamic method because it better shows the potential impact of active power curtailment on voltage flicker mitigation.

Grid reinforcement aims to lower the resistance R in [Eq. 1], and thus making the system less vulnerable to changes in power output of the solar PV systems. Grid reinforcement can be done by either placing new cables or redirecting old cables to reduce their stress (Stetz, Marten & Braun, 2012). Different cable types all have different corresponding resistances. For instance, replacing a common GPLK 4x25mm Curm cable by a 4x150mm VVMvKhas/Alk 4x6 cable would reduce the resistance in the cable by about 72%. This would theoretically also reduce the voltage fluctuations in this cable by 72% according to Equation 1. Section 3.2. elaborates on this. Redirecting a cable can be done by splitting a cable at a weak point in the grid and redirecting both ends to different, stronger points in the grid to reduce the amount of active power P flowing through these cables which would also result in lower voltage fluctuations according to Equation 1. This thesis first looks at the effect of replacing the cables, when a weak point in the LV grid is found. This is then solved by redirecting this stress away from this specific weak point.

Similar to active power curtailment, EES technologies also aim to limit $|\Delta V|$ in [Eq. 1] by limiting changes in active power dP. However, the method is different. EES technologies can be used to delay the feeding of the active power into the grid by storing it temporarily. The EES technology can be programmed to store or to release active power when there are rapid changes in power production, thus limiting the voltage fluctuations. EES technologies do have efficiencies which have to be taken into account. A charge/discharge cycle reduces the total amount of active power that can be dissipated into the grid. This thesis looks at using a supercapacitor as an EES technology. Reasons to choose supercapacitors include that they can be quite easily placed throughout the LV grid because of their small size and because supercapacitors have the ability to react almost instantaneously to changes in voltage, which enables it to react to a rapidly changing PV power output (Sahay & Dwivedi, 2009). Furthermore, supercapacitors generally have a large specific power which enables them to quickly store much energy and it can store this power for about 30 minutes (Argyrou et al., 2018). This is more than enough time to slowly feed in the stored power back to the grid. The capacity of a supercapacitor can be quantified according to Equation 2. Where E equals the capacity of the supercapacitor in Wh, C equals the capacitance of the supercapacitor in Farads F and V equals its operating voltage. Equation 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 resulting from solar PV, it should have a large enough capacity to store enough energy for a specific period and it should have a large enough power to be able to store all power produced by the solar PV system if required.

$$E = \frac{1}{2} C * V^2 \qquad \text{[Eq. 2]}$$

3. Case study: Lombok area

This section describes the geographic and technical characteristics of the case study. The information in this section is used for interpretation, explanation and discussion of the results. First, this section describes the analyzed Lombok area in general in order to understand what type of neighborhood has been analyzed. Afterwards, an overview of the type of electrical equipment present in the area is provided. This overview is necessary for this and future research to be able to put the results for this case study into perspective.

3.1. General overview

The case study that was analyzed in this thesis is part of the Lombok neighborhood in center-west Utrecht, The Netherlands. More specifically, this case study is part of the south of the Lombok area which is connected to a transformer station located at the Floresstraat. The Lombok area is a densely populated urban area with about 18,033 people per km^2 (CBS, 2017), which is the third densest area in Utrecht. The inhabitants are primarily young and multicultural, 67% of the inhabitants was between 15 and 44 years old in 2017 (NL total; 37%) and 37% is not from the Netherlands (NL total; 23%) (CBS, 2017). The area analyzed consists of 343 grid connections, which is 7.5% of the total amount of grid connections in the Lombok area (CBS, 2017). Amongst these 343 grid connections, 323 grid connections are households, two are kindergartens, one is an elementary school and seventeen are shops. Public charging points are disregarded for simplification purposes. A map of the area is presented in Figure 2. The red line encloses the entire Lombok area, the yellow line encloses the part of the area that was studied.

Figure 2: Lombok area (Google Earth Pro, 2019)

Since there are many one floor apartments in the analyzed area, not all grid connections have the potential for PV systems to be installed. 215 of the 343 grid connections have a roof suitable for solar PV systems. Currently, 13 of the 343 grid connections (4%) have a solar PV system installed, this is lower than the Dutch average of 13% (van Gastel & de Jonge Baas, 2019). The total amount of installed PV systems was determined through Google Earth images taken on 24 August 2019 (Google Earth Pro, 2019).

3.2. Technical overview

The entire area analyzed in this thesis is connected to one MV/LV transformer. The transformer is a 10kV/0.4kV transformer with a capacity of 400 kVA. Within the area, there are eight distribution sub-stations, which connect all 21 cables. A total of 445 nodes are present, each node has the possibility of a (household) grid connection and the 343 grid connections are all connected to individual nodes.

The equipment within the analyzed area is relatively old; most cables in the Lombok area have been installed over 60 years ago. 91% of the 445 nodes present in the system are still connected to a GPLK type cable, which have not been installed for grid purposes in the Netherlands since the 1980's (van Oirsouw, 2012). The remaining 9% of the cable pieces are of the VVMvKhas/Alk 4x6 type. The VVMvKhas/Alk 4x6 cables are mostly present close to the transformer. Since most load has to travel through these cables, these were replaced after the 1980's because of an increase in electricity consumption. Besides the different types, the cables also have different diameters throughout the area. The thicker the diameter, the lower the resistance R in the cables. An overview of the cable types present in the area and their corresponding resistances is presented in Table 1. From Table 1, it can furthermore be deduced that the distance between nodes on the cables is larger for thicker cables.

Table 1: Cable types and resistances

Cable Type	**Resistance [Ω/km]**	**Nodes [amount]**	**Total length [m]**
GPLK 4x6mm Curm	3.061	14	33
GPLK 4x25mm Curm	0.726	182	1050
GPLK 4x50mm Cusvm	0.387	72	370
GPLK 4x70mm Cusvm	0.269	125	957
GPLK 4x95mm Cusvm	0.195	12	184
4x50mm VVMvKhas/Alk 4x6	0.641	16	258
4x95mm VVMvKhas/Alk 4x6	0.320	6	69
4x150mm VVMvKhas/Alk 4x6	0.206	18	319

4. Methods

This section describes the methodological steps that are taken in order to answer the research question. This section has been split up into four separate parts. Firstly the three different research steps are discussed separately, including the data required, software used and analysis performed. Afterwards, the reliability and validity of the research are discussed.

4.1. Step 1: assessing the current situation

The first step of this research is to assess the current problem of voltage flicker for a specific part of the Dutch LV grid. This is done for the neighborhood Lombok in Utrecht, which is composed of 343 household grid connections. 215 of these households have the possibility to install solar PV systems, and currently 13 households have done so. A more elaborate description of the case study can be found in Section 3. In order to model this part of the LV grid, Python 3.7 (Python Software Foundation, 2019) and the grid model software DIgSILENT PowerFactory 2019 SP2 (DIgSILENT GmbH, 2019) are used, from now on referred to as Python and PowerFactory.

The model was built in the grid modeling software PowerFactory. This software has the ability to draw and simulate a grid while assigning specifications to each component in the grid. The Lombok area modeled in this thesis consists of one 10kV/0.4kV transformer, 8 distribution sub-stations, 21 LV cables and 343 loads. Each of these components has individual characteristics such as type, capacity, resistance and cable length. The characteristics of each component were obtained through Stedin, a Dutch DSO. A visual presentation of the model can be seen in Figure 3. The colored lines represent the different cables, the small vertical stripes represent the household grid connections and the squares represent distribution sub-stations. Of these sub-stations, six are visible in the figure because they connect more than two cables, two only connect two cables and are therefore not visible in Figure 3. The large rectangle represents the transformer. Each of the 343 loads was assigned with an electricity demand profile and potential PV production profile (to be switched on or off) if the household connection has the potential to place panels. A more detailed insight in how these profiles were generated and assigned to the different grid connections can be found in Section 5.

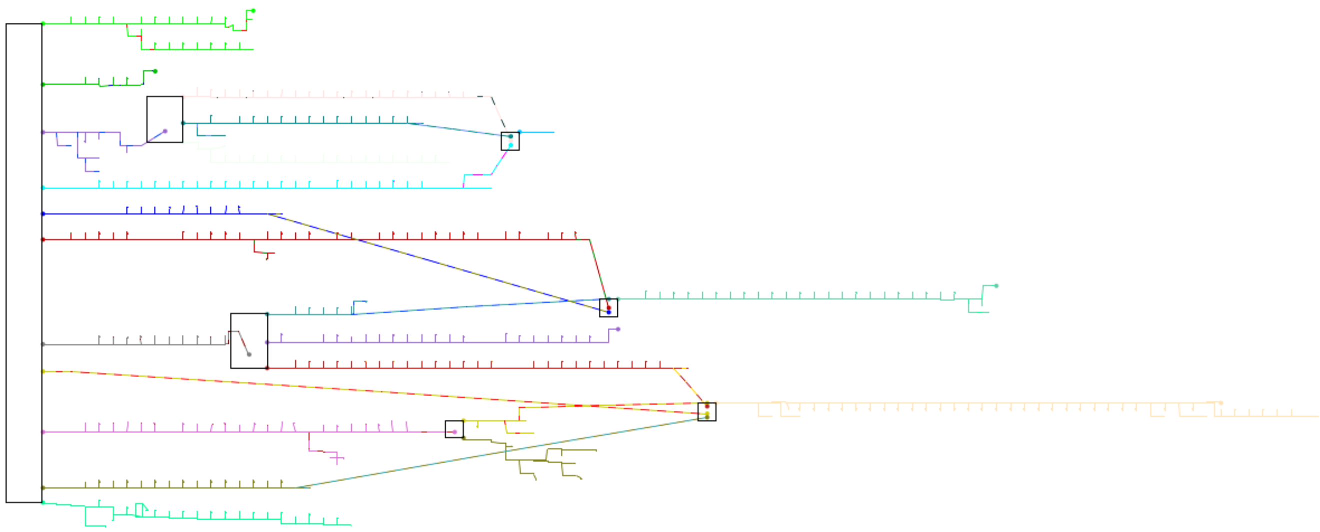

Figure 3: LV grid attached to MV/LV transformer at Floresstraat, Lombok, Utrecht modeled in PowerFactory

The analysis performed in PowerFactory is a quasi-dynamic load-flow simulation, assuming a perfectly balanced load over the three-phase cables. The perfect balance is assumed because the data about connections and corresponding phases is unavailable. This simulation performs an individual load flow analysis for each point in time, in this case 43200 simulations for every two seconds during one day (i.e., 4 August 2017). The choice for this specific date is explained in Section 5.1. The reason to assume a perfectly balanced load over the three phases of the cables is that it is uncertain how the loads will be divided over the phases with an increasing PV capacity. Furthermore, it is assumed that the MV grid connected to the analyzed LV grid does not cause extra voltage fluctuations, which in reality it does. The choice for this assumption is based on the absence of MV grid data and the uncertainty on how the effect of the MV grid on the LV grid will change with an increasing installed solar PV capacity. The quasi-dynamic load-flow simulation gives a voltage profile as a result for each pre-selected part of the grid. In order to save computing time, twelve relevant parts of different cables were selected to be analyzed. An overview is provided in Table 2. The choice was made to compare cables with only household grid connections to be better able to compare the effect of technical differences between the different cables. The numbers in Table 2 correspond to those in Figure 4.

Table 2: Cables analyzed in PowerFactory

Numbers	Cable Type	Reason to analyze
1 & 2	GPLK 4x70 & GPLK 4x50	At this point, the cable becomes narrower (a 70mm diameter becomes a 50mm diameter cable). Analyzing the voltage just before and just after the narrowing shows the effect the diameter of a cable has on the voltage fluctuations.
3 & 4	GPLK 4x50	This cable is the cable which is furthest away from the transformer. The points measured are the beginning and end of the cable. It is expected that the large fluctuations occur furthest from the transformer.
5 & 6	GPLK 4x25	This is the narrowest long cable in the grid with quite some loading attached (19 household grid connections and all houses have the possibility to install a solar PV system). The points measured are the beginning and end of the cable. Large fluctuations are expected to occur in narrow cables with a lot of loading.
7, 8 & 9	GPLK 4x70	This cable is one of the longest cables and the one with most household grid connections (34). Measurements at the beginning, middle and end of the cable shows the effect that the place in a cable has on the voltage fluctuations.
10 & 11	GPLK 4x70	These measurements are a long cable with much potential for PV systems (17 suitable households) and a short cable with little potential for PV systems (4 suitable households). But the cable type is equal for both measurements. This shows the effect of loads on a cable.
12	0.4kV busbar	This measurement represents the voltage at the transformer at the LV side. At the transformer, little fluctuations are expected.

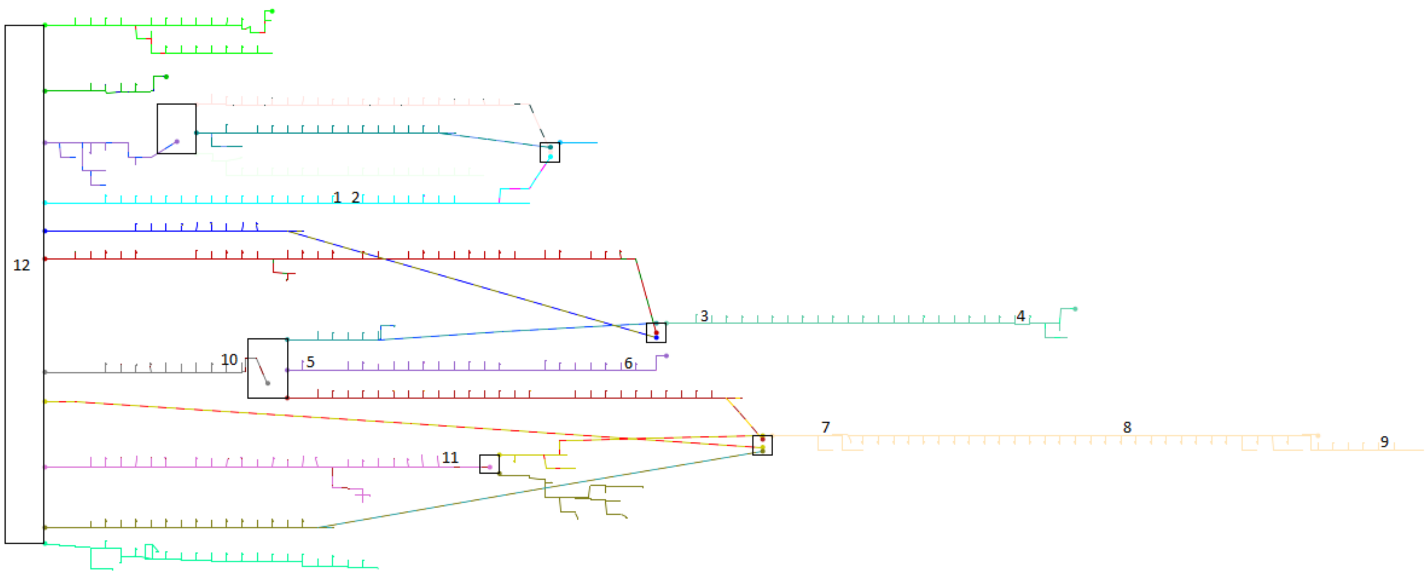

Figure 4: Measuring points in the LV grid attached to MV/LV transformer at Floresstraat, Lombok, Utrecht modeled in PowerFactory

The voltage profiles of the pre-selected cable parts were extracted from PowerFactory and used for two types of analysis. First, the voltage profiles were plotted in order to get visual insights in the magnitude and frequency of the voltage fluctuations. Afterwards, for each point in time the $|\Delta V|$ value was determined according to Equation 3.

$$|\Delta V|_i = |V_i - V_{i-1}| \qquad \text{[Eq. 3]}$$

The results for Equation 3 were used to assess for what percentage of time the voltage flicker is visible $|\Delta V| \geq 0.826V$ and what percentage of time the voltage flicker is irritating $|\Delta V| \geq 1.927V$. These results were then presented in a table and in a plot where the $|\Delta V|$ values are sorted on severity. The results combined give an indication of the severity of the voltage flicker problem.

4.2. Step 2: exploring voltage flicker for different PV penetration rates

In this step, the model from Step 1 is run again, considering three scenarios for the amount of solar PV systems installed in the area. These scenarios are used to compare to what extent the problem of voltage flicker increases with an increase in the number of PV systems installed. Currently 6% of the houses that can install solar PV systems in the Lombok area have PV systems installed. This corresponds to 4% of the total households, which is less than the Dutch average of 13% (van Gastel & de Jonge Baas, 2019). The scenarios used in this thesis regarding the solar PV penetration rates are the following:

- Scenario 1 (100%): The reason to choose 100% as the percentage of households with solar PV is to assess the maximum impact of solar PV to a part of the Dutch LV grid, and to see if in this case the to be analyzed solutions can still mitigate the voltage flicker.
- Scenario 2 (70%): The reason to choose 70% as the percentage of households with solar panels is based on the prediction made by the Dutch urban planning agency (PBL) and the Dutch central statistics agency (CBS) who predict that there will be 10 TWh solar energy production from residential areas by 2030 (PBL, 2019). Currently there is 1.9 TWh solar energy production from residential areas (13% of all households) (CBS, 2018). This translates to almost 70% of households with solar panels, assuming similar solar PV capacity per household.
- Scenario 3 (40%): The reason to choose 40% as the final scenario is that currently PV systems are only installed on 6% of the households with a roof. This is significantly lower compared to the 13% Dutch average. Since this specific location is below the Dutch average, this scenario assumes that this will remain to be the case with an increasing solar PV capacity.

The houses on which new solar PV systems will be installed is determined through randomization. The sizes of the PV systems to be added are randomized using a normal distribution with an average size of 3.6 kWp. The reason to choose 3.6 kWp is based both on calculations made by the European Commission, who estimate the average residential PV system potential in the Netherlands to be 4.25 kWp (European Commission, 2017), and on calculations by van Sark (2019) who calculated the Dutch urban PV systems to be 3.4 kWp on average. This thesis assumes that the average size of newly installed systems is higher than the current average, but not as high as the potential calculated by the European Commission. This assumption was made because estimation by the European Commission is for all Dutch household solar PV systems and not only for urban ones and the urban solar PV systems are generally smaller. The standard deviation for the normal distribution used is 1.0 kWp. This resulted in the system sizes to be varying between 0.9 kWp and 6.4 kWp, which roughly translates to 3 to 22 panels, which are extreme but not unrealistic urban PV system sizes. Running the PowerFactory model for the three separate scenarios results in the same type of output as described in Step 1.

4.3. Step 3: exploring possible solutions

In this step, the model from Step 2 is expanded three separate times to include each of the different voltage regulation techniques individually. Each of the different options has a different methodology in order for it to be included in the PowerFactory model. These methods are discussed in this section. The different options are primarily assessed on its ability to mitigate voltage flicker. Moreover, additional technical implications such as "lost" power and requirements for technical components are discussed.

4.3.1. Option 1: active power curtailment

Active power curtailment of PV systems is mostly used as a measurement against overloading the grid. This is done by reducing the active power output of the PV systems when components in the electricity grid are in danger of having to process more power than they can safely handle. This thesis uses active power curtailment in a different way, namely to curtail active power based on the voltage fluctuations present. ΔV values are used in order to do so. Whenever rapid voltage fluctuations are present because of an increase in active power in the grid, the active power output of the PV systems is curtailed. This is done in a linear way, starting with a 0% curtailment up until a ΔV value of 0.70V until 50% curtailment at the largest voltage increase present at 4 August 2017 in each of the scenarios, ΔV_{max}. Furthermore, the PV power output is curtailed preventively to anticipate to sudden drops in PV power output. Whenever ΔV is smaller than -0.70V, it is linearly curtailed at the previous time step from 0% at -0.70V to 50% at the larges voltage decline present at 4 August 2017 in each of the scenarios, ΔV_{min}.

This option is included in the PowerFactory model by using the model output from the situation without interference, determining the new power output of the PV systems in Python, and afterwards feeding these new PV production profiles back to PowerFactory. The results from the new PowerFactory run show the new flicker values which are then used to determine the percentage of flicker reduced. This new profile experiences voltage flicker at different times since curtailing PV at a certain time t_n can result in a larger voltage fluctuation at t_{n-1} or t_{n+1}. Therefore, this new profile is curtailed again. This process is repeated five times for each scenario. The choice for five iterations is made because of a limited time and computing power available. The "lost" power in this scenario is determined by comparing the solar PV power production profile of the initial scenario to the profile after five iterations. The difference between the profiles is the total amount of power curtailed.

4.3.2. Option 2: Grid reinforcement

As described in the Section 2., reinforcing the grid can also reduce voltage fluctuations. Better, or shorter cables lead to a lower resistance in the cable, which lead to smaller voltage fluctuations according to [Eq. 1]. The choice was made to replace all the cables present in the Lombok area with the 4x150mm VVMvKhas/Alk 4x6 cable, since Table 1 shows that this is the cable with the lowest resistance which is still being placed (as described in Section 3.2, the GPLK cables are not used anymore). The reason to choose to replace all cables present is that it shows the maximum effect that grid reinforcement can have. When the grid reinforcement is sufficient to mitigate all voltage fluctuations, it is assessed whether thinner cables can also have this effect. When the maximum effect is not sufficient, there is no reason to analyze strategic reinforcement of cables. Furthermore, it is assessed whether there are some weak places in the analyzed grid. If this is the case, stress is relieved from these places by redirecting cables.

This option is performed in PowerFactory. Here, each cable type is changed manually. After the cable types are changed, the same simulations as in step 2 are performed. Afterwards, the results are compared in order to identify the amount of voltage flicker that is reduced.

4.3.3. Option 3: Electrical Electricity Storage (EES) – Supercapacitor

Supercapacitors are ideal for voltage regulation of solar PV systems because of their ability to react very quickly and because they have large charge/discharge capacities (Argyrou et al., 2018; Espinar & Mayer, 2011). The supercapacitors used in this thesis are placed between the solar PV systems and the inverters in order to avoid an extra AC/DC conversion. The supercapacitor is used to smoothen the PV power output. The output is smoothened by simulating the supercapacitor in such a way that its power output equals the moving average of the initial PV profile. A supercapacitor is able to provide such an output when its size and charge/discharge capacities are sufficient (Carvalho, Bataglioli & Coury, 2018; Chong et al., 2017). However, one does not want to oversize their supercapacitor since that would mean unnecessary costs and room required. Therefore, an optimal size of the supercapacitor was aimed to find in each scenario by assessing how much voltage flicker is present in the system when taking the moving average over different time periods. The larger the time the supercapacitor has to store the power, the larger the size of the supercapacitor has to be. The time periods used for the moving average are 6, 10 and 20 seconds, which equal 3, 5 and 10 2-second time-steps respectively.

The requirements of the supercapacitor were determined by first subtracting the initial PV profile P_1 from the smooth PV profile P_2. The required charge/discharge capacity equals the maximum charge/discharge required and the size of the system was determined by taking the integral of $P_2 - P_1$ and using this to find the minimum and maximum charge of the supercapacitor. Python was used to alter and assess the supercapacitor related PV profiles. The supercapacitor does experience "lost" power because of charge and discharge efficiencies and the efficiency of the DC/DC converter required for using the supercapacitor. However, because of the fact that these efficiencies depend on numerous factors, such as resistance within the capacitor, operating voltage, frequency, temperature and current (Maxwell Technologies, 2009) and because each solar PV system would require a different supercapacitor, it is not possible to determine the exact losses. Therefore, an estimate is provided in Section 6.3.3. based on literature and product specifications.

4.3. Reliability and Validity

This research aims to achieve high validity and reliability. In order to increase the reproducibility of this research, and therewith increase its reliability, formulas and relationships used in the modeling process are provided within the thesis. The PV data used cannot be shared in the thesis for privacy reasons. This limits the reproducibility. However, similar results are likely to be obtained when PV data for a different location in the Netherlands are used. The same reasoning holds for the demand data and grid specifications, which cannot be shared due to their sensitive nature. This thesis uses the software DIgSILENT PowerFactory 2019 SP2 and Python 3.7. Python is open source. PowerFactory is not free, but it is available to anyone who purchases it. This slightly limits the reproducibility of the research. This research does not aim to generalize the results for this specific case study, this limits the validity of the research. However, it does show the possible impact of different voltage regulation techniques, which is valuable.

5. Input data

This section describes the process to generate the input data for the model. This section is split up into two separate parts, PV data generation and demand data generation. For each of the data-types the input data used is described, as well as the process to convert this input data to usable data for the model.

5.1. Generating solar PV production profiles

In order to map the current situation, for each grid connection a PV production profile has to be generated. Since shading by cloud movement does not happen equally throughout the area, using the same PV production profile for each household would not be a realistic representation of the actual PV power production in the area. Therefore, individual profiles are required to be able to adequately represent the Lombok area. In order to generate these individual profiles, 2-second PV production profiles for four locations in Lombok were used. These profiles were obtained through Utrecht University. The location of the PV production profiles can be seen in Figure 5 (blue indicators). The area enclosed by the yellow line shows the Lombok area that was analyzed in this Thesis. As can be seen, the PV systems of which data are available are not located within the yellow area. In order to be able to generate realistic PV profiles for each household connection, the four PV systems were assumed to be within the Lombok area that was analyzed. Figure 6 shows how the four PV systems were replaced. The distance among the different systems was kept the same to ensure the generation of realistic profiles.

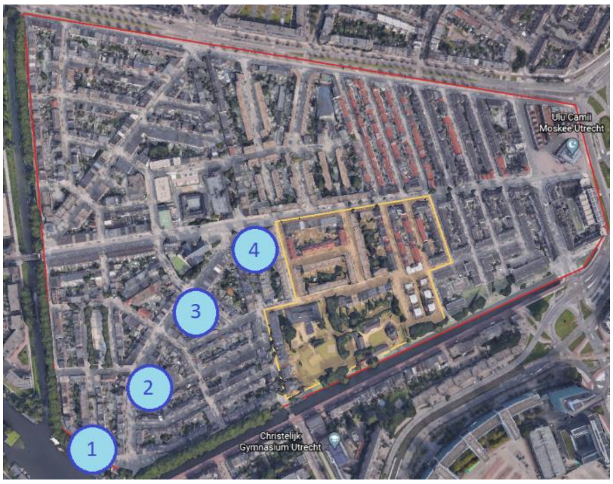

Figure 5: Location of the PV systems

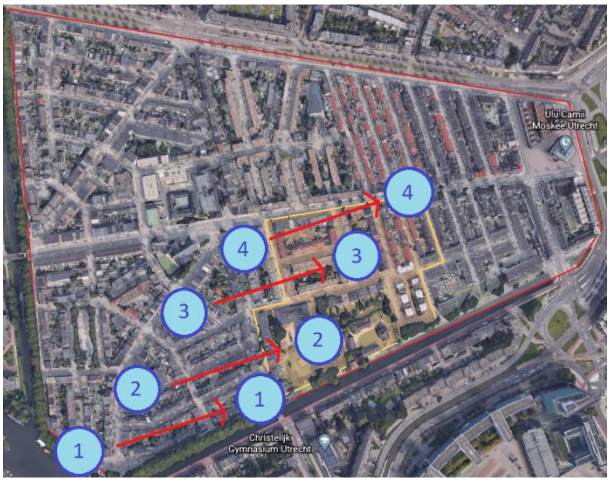

Figure 6: Assumed location of the PV systems

The decision was made to choose the solar PV profile for 4 August 2017. The reason to choose this date has been that this is a day with a rapidly fluctuating PV output, as can be seen in Figure 7. Furthermore, Figure 7 shows the PV profile of the day with most solar PV generation in 2017 to put the fluctuations of 4 August 2017 into perspective. The situations in which 4 August produces more power than the day with most PV generation is a result of cloud enhancement, Figure 7 shows that this happens often in 4 August 2017. Moreover, 4 August 2017 has the largest total power fluctuations of all days in 2017, as can be seen in Figure 8. The power output in Figure 7 seems to be capped at 100%. However, this was not done deliberately in this thesis. A potential reason for this could be a slightly undersized inverter.

Since the power quality should always be sufficient, it should be able to withstand an extreme day like 4 August 2017. The decision to study only one day has been made because of a limited computing power and limited demand data available.

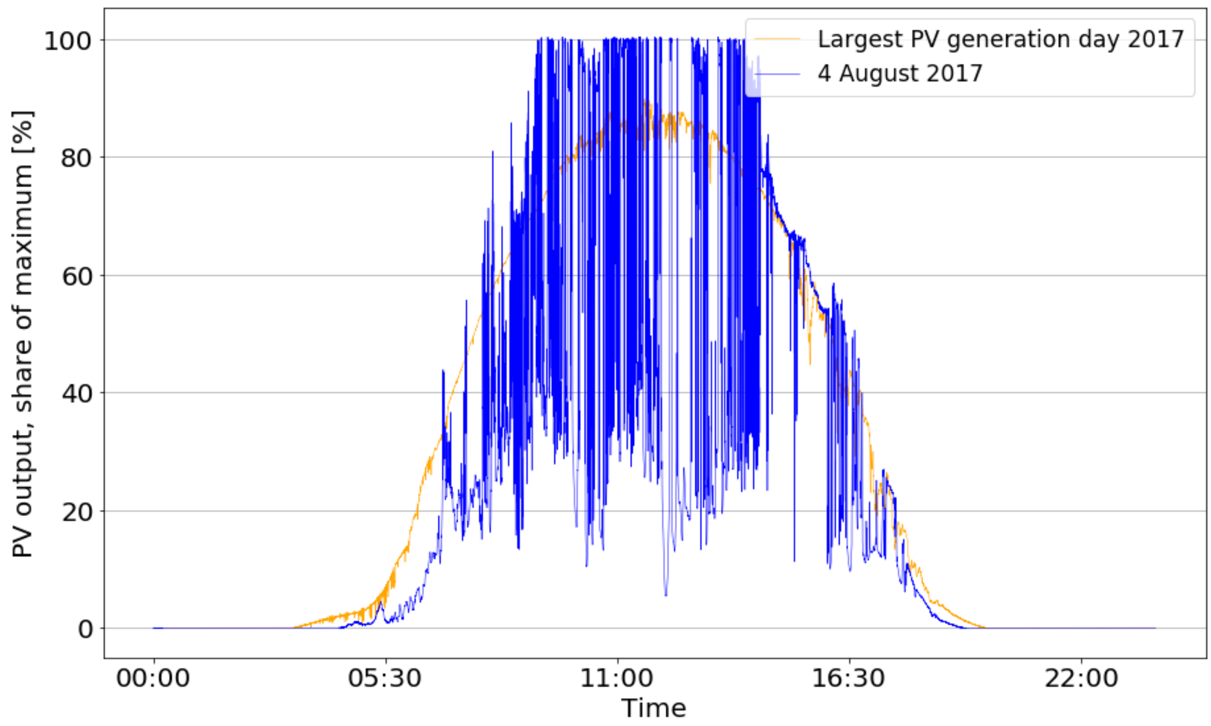

Figure 7: PV profile 4 August and largest PV generation day 2017

Figure 8 illustrates how 4 August 2017 relates to other days in 2017. In Figure 8a, each dot represents a day, in Figure 8b, each dot represents 30 minutes. The x-axis shows how much power was produced at each day/30 minutes ($\sum P$), relative to the day/30 minutes where most power was produced. The y-axis shows the total power fluctuations at each day/30 minutes ($\sum |P_i - P_{i-1}|$), relative to the day/30 minutes with most power fluctuations.

Figure 8a shows that 4 August 2017 is an extreme day compared to the average day, but that there are multiple days with severe power fluctuations. 32 other days (9% of all days) experience at least 40% of the fluctuations of 4 August 2017, and these days are spread throughout spring, summer and fall. This shows that the fluctuations are not just concentrated in a few days. Furthermore, Figure 8a shows that at a low power production <30% or a very high power production >95%, less severe fluctuations occur. This can be explained by that at low power production there is less solar radiation coming in and thus less chance for rapid power fluctuations. At very high power production there are most likely very few clouds that can result in rapid power fluctuations.

Figure 8b shows similar behavior to Figure 8a, the largest fluctuations are also concentrated between 30% and 95% of the maximum power production. The difference between the figures is that in Figure 8b, there are much more points at which there is at least 40% of the maximum fluctuations. 161 of the 30 minute sums experience at least 40% of voltage fluctuations compared to the most heavily fluctuating 30 minutes. These fluctuating times are spread throughout spring, summer and fall, which again shows that the fluctuations are not just concentrated at a certain point throughout the year.

The Average values in Figure 8a and 8b are equal. The fact that in Figure 8b, the average has shifted towards the bottom left corner of the figure suggests that the 30 minute values in Figure 8b are much more extreme compared to the daily values in Figure 8a.

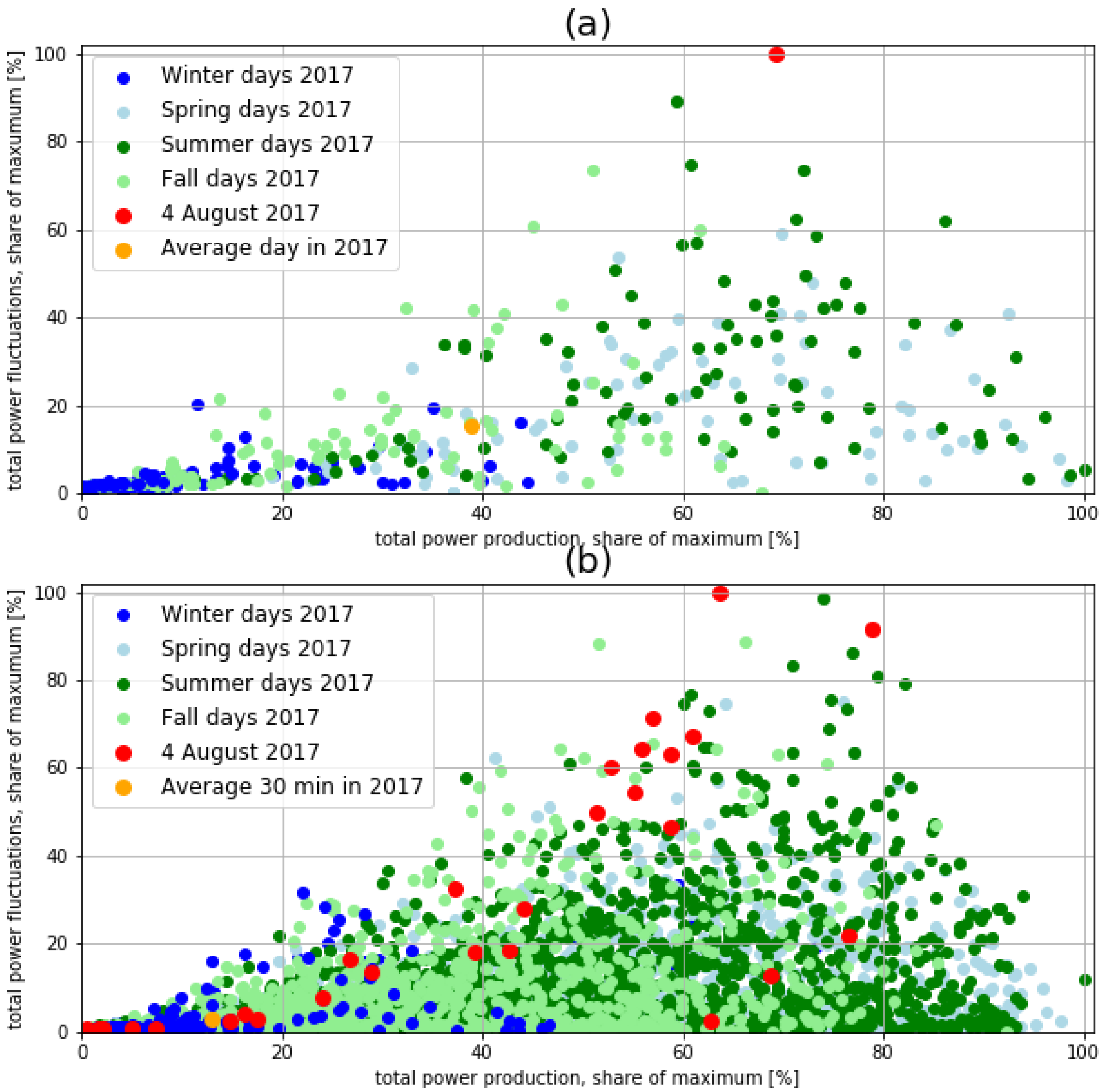

Figure 8: a) Power production and power fluctuations in 2017 - daily sums b) Power production and power fluctuations in 2017 – 30 minute sums

The PV production of each individual household was determined through interpolation of the normalized PV data of the four locations. The interpolation method that was used is inverse distance weighted interpolation. This method interpolates data based on surrounding values. It assigns a weight to each surrounding point based on the distance from the to be interpolated point to the surrounding points. The reason that this method is chosen is because it is most commonly used in environmental sciences and because it allows for multiple location inputs to be used, which makes the method more complex, but also more accurate compared to linear interpolation (Li & Heap, 2011). Inverse distance weighted interpolation has also been used in forecasting solar PV power production (e.g. Bofinger & Heilscher, 2006; Yang et al., 2014). However, this was done for larger areas and larger time steps compared to this thesis. A disadvantage of this interpolation method is that the generated PV profiles are more smooth compared to the actual situation. Kriging is an interpolation method which overcomes this disadvantage and it has also been used and recommended as an interpolation method for solar PV power production (Yang et al., 2014; Di Piazza, Di Piazza & Vitale, 2009; Jamaly & Kleissl, 2017). However, four data points is too little for kriging to provide a realistic output, at least 30-50 points are required for this method (Webster & Oliver, 1993). Therefore, the choice was made to use the inverse distance weighted interpolation method.

In order to be able to interpolate the PV-data, the Lombok area was divided into 10m x 10m squares. Since the Lombok area that was analyzed is 310m x 260m, a total of 806 unique PV-profiles had to be constructed. Within the 31x26 grid that was formed, the four PV locations were placed; System 1 [1, 31], System 2 [9, 22], System 3 [14, 10] and System 4 [24, 1]. Since the four PV production profiles are based on systems with different sizes, the profiles had to be normalized before they could be used. This was done by dividing all production values by their installed capacity, which is considered to be equal to the 99.9th percentile to exclude the effect of outliers in the data. These outliers can either be faulty measurements or a result from cloud enhancement, which can result in a PV system producing more than 100% of its capacity (Gueymard, 2017). The orientation and tilt are assumed to be equal for all generated PV systems. This choice was made because of the absence of data of the tilt and orientation of roofs in the Lombok area and because of limitations in (computing) time. The PV production profiles were created using [Eq. 4] for each individual time step i.

$$PV\_production_i[W] = \frac{\frac{P1_i}{D1}+\frac{P2_i}{D2}+\frac{P3_i}{D3}+\frac{P4_i}{D4}}{\frac{1}{D1}+\frac{1}{D2}+\frac{1}{D3}+\frac{1}{D4}} \quad \text{[Eq. 4]}$$

Where P_1 through P_4 are the PV profiles of System 1 through System 4, and D_1 through D_4 are the distances of a location to the systems. D_1 through D_4 are determined through Pythagoras, and were determined using Equation 5 through 8.

$$D_{1,i}[m] = \sqrt{(Y_i - 310)^2 + (X_i - 10)^2} \quad \text{[Eq. 5]}$$

$$D_{2,i}[m] = \sqrt{(Y_i - 220)^2 + (X_i - 90)^2} \quad \text{[Eq. 6]}$$

$$D_{3,i}[m] = \sqrt{(Y_i - 100)^2 + (X_i - 140)^2} \quad \text{[Eq. 7]}$$

$$D_{4,i}[m] = \sqrt{(Y_i - 10)^2 + (X_i - 240)^2} \quad \text{[Eq. 8]}$$

Where Y_i and X_i are the vertical and horizontal distances in meters. After the PV-profiles were generated, every household was assigned with a PV-profile based on the location of the household. The location of each household was determined using Figure 30 in Appendix A.

5.2. Generating household demand profiles

Besides a PV production profile, each household connection also requires an electricity demand profile. The household demand profiles were constructed using data obtained through Stedin. Through a week-long smart metering pilot among Stedin employees in 2019 and 2020, 1-minute resolution electricity demand data was collected. A number of these Stedin employees have given approval to use this data anonymized in this Thesis. Four week-long 1-minute electricity demand profiles were obtained. From these data, all weekdays were selected and used as individual profiles. This resulted in 25 individual profiles, which is less than the 343 households in the analyzed Lombok area. The remaining profiles were generated by delaying and forwarding the existing profiles with two-minute time steps.

After the electricity demand profiles were obtained, the 1-minute resolution data had to be transformed into 2-second resolution data. This was done through linear interpolation. This does limit the possibility for sharp peaks in the electricity demand data, but it does resemble the actual situation better compared to randomizing demand profiles.

Figure 9 shows the average electricity demand of all household grid connections. The figure shows a peak in electricity demand between 17:30 and 19:00. This can be explained by the extra electricity required for cooking.

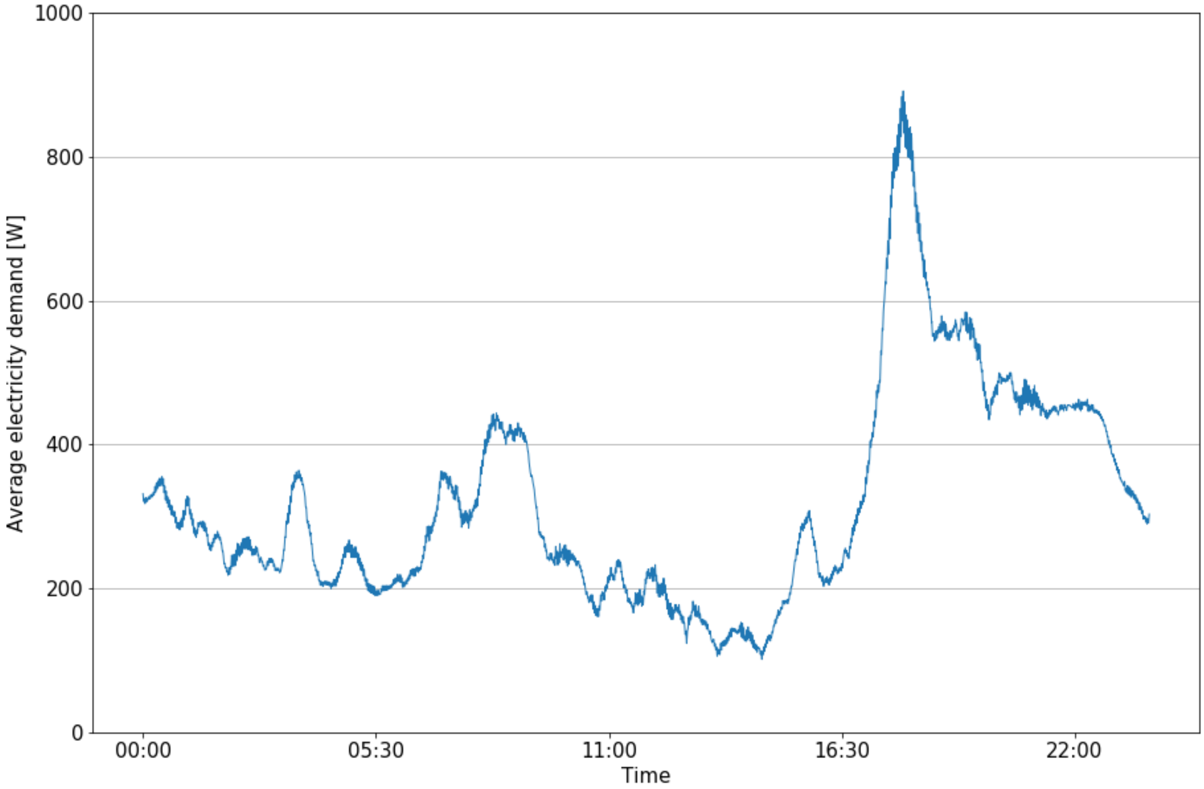

Figure 9: Average household electricity demand used to simulate 4 August 2017

6. Results

In this section, first the results for the current situation are discussed, followed by the scenarios and solutions. This is done by briefly repeating each research step and then the presenting the results, flicker values and voltage profiles. Afterwards, the results are interpreted and compared. The results are later used to for the conclusion and discussion.

6.1. Assessing the current situation

The current situation represents the results with the current amount of solar PV systems installed in the Lombok area (13 systems, 6% of the households which can install PV systems, 4% of all households). Figure 10 shows both the voltage profile generated by PowerFactory for 4 August 2017, and the ΔV profile which corresponds to this profile. Figure 10b shows that the most rapid voltage fluctuations are present between 08:00 and 16:30, this timeframe is also the timeframe in which solar PV power production is highest, as can be observed in Figure 7. This confirms the suspicion that the most significant voltage fluctuations are a result of solar PV output. Since a perfect balance in the attached MV grid is assumed in this thesis, a voltage of exactly $230V$ would mean that there is just as much PV power production present as there is demand. When the voltage is lower than $230V$, there is more demand than PV production and vice versa. Figure 10a shows that there is more power production than demand between 09.00 and 16.30. The drop in voltage in Figure 10a around 17.30 until 19.00 is a result from a an increase in electricity demand, as can confirmed by Figure 9. This is most likely a result from an increase in electricity use for cooking.

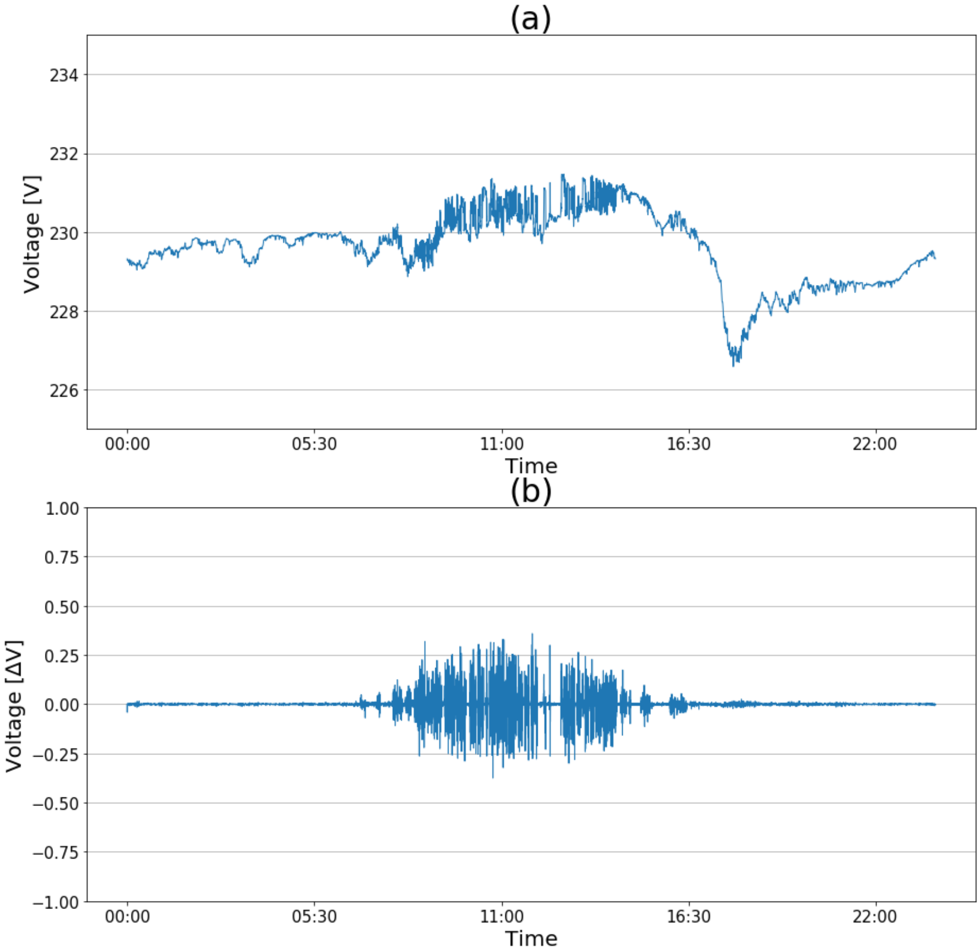

Figure 10: a) Voltage profile 4 August 2017 in the current situation b) Voltage fluctuations 4 August 2017 in the current situation

Figure 11 shows the $|\Delta V|$ values for the 2000 most heavily fluctuating time steps for all of the analyzed lines sorted by severity. Line 6 is highlighted because it shows the largest voltage fluctuations. The choice was made to only look at Line 6 in further analysis because of the assumption that if voltage flicker can be mitigated in the most heavily fluctuating line, it can be done for all cables in the Lombok LV grid. Figure 11 shows that Line 6 is not just an outlier, there are multiple lines with a similar magnitude of voltage fluctuations present. The bottom outlier represents the voltage fluctuations at the transformer, which is built to withstand a lot of power flowing through and therefore experiences only little voltage fluctuations. Figure 11 furthermore shows the thresholds for visible and annoying voltage flicker. It can be observed that at the voltage fluctuations in the current situation do not exceed the thresholds. Hence, it can be concluded that no voltage flicker is present in this situation.

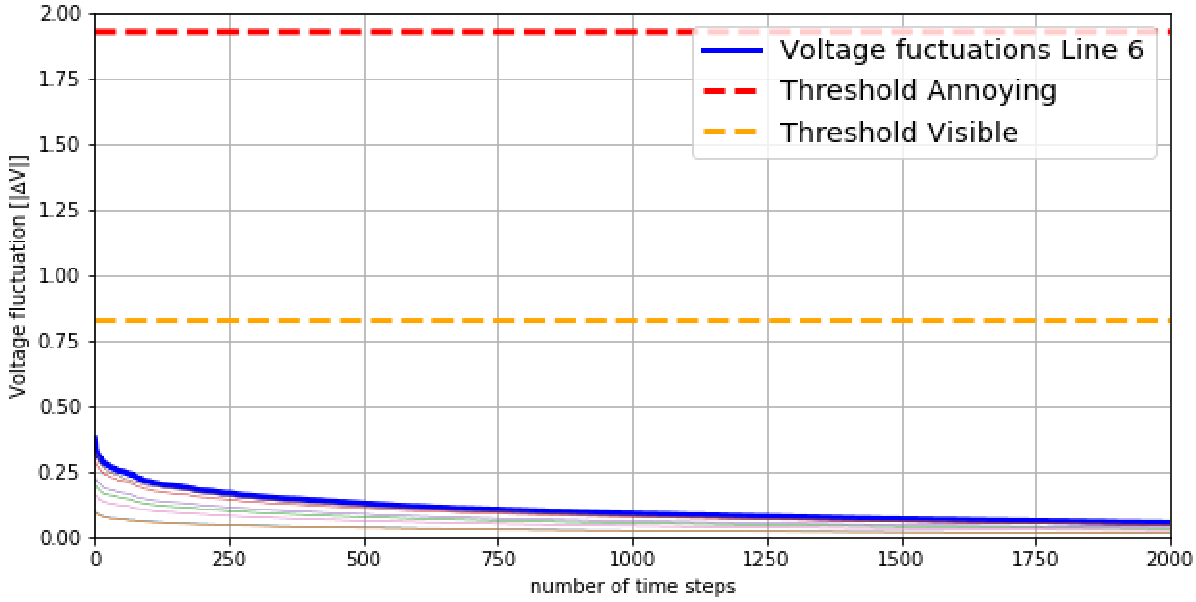

Figure 11: Voltage fluctuations 4 August 2017 sorted by magnitude

6.2. Exploring voltage flicker for different PV penetration rates

This section describes the results for the scenarios with 40%, 70% and 100% PV penetration rates. Figure 12 shows both, the voltage profiles of these scenarios generated by PowerFactory for 4 August 2017, as well as the ΔV profiles which correspond to these profiles. When voltage profiles from Figure 11 are compared to voltage profile from Figure 10, it can be observed that the voltage reaches higher values, the larger the PV penetration rate. This is a logical result from the fact that with more solar PV systems, there is a larger solar PV output. The larger the output, the more stress on the cables, the higher the voltage gets. However, it can be seen that the maximum voltage remains lower than the 253V threshold for voltages in the LV grid. The voltage profiles 12a, 12c and 12e furthermore show that the voltage only increases in times of significant PV power production, the higher PV penetration rates did not affect the drop in voltage between 17.30 and 18.30 because there was no significant PV power production at this time.

The magnitude of the voltage might not be a problem in the scenarios, but this does not mean that there are no problems with rapid voltage fluctuations. Figures 12b, 12d and 12f show that the voltage fluctuations increase rapidly as the PV penetration rate increases as well. In the 100% PV scenario, largest the voltage fluctuations even exceed 4V, which is much higher than the thresholds for visible and annoying voltage flicker.

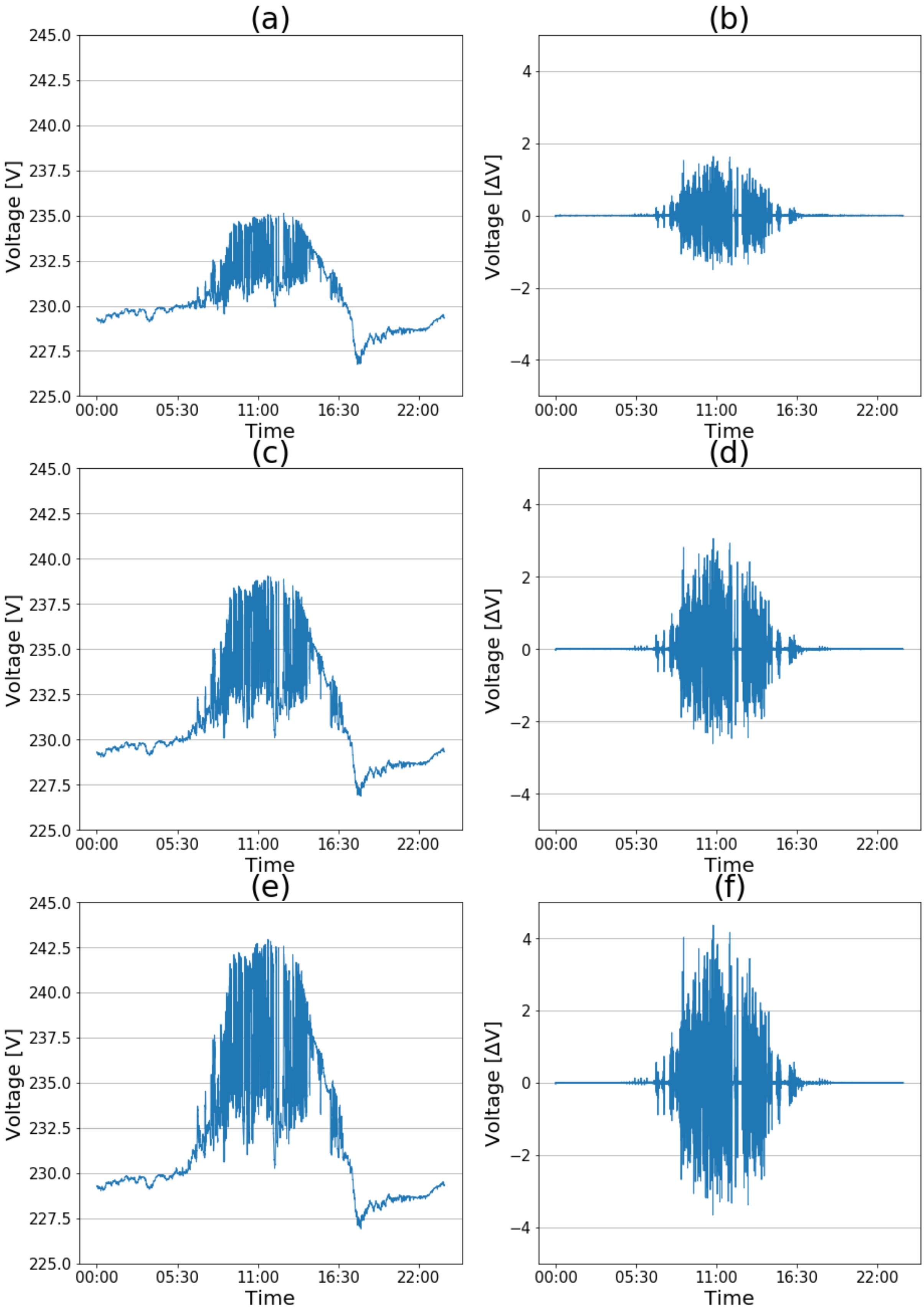

Figure 12: a) Voltage profile 40% PV scenario b) Voltage fluctuations 40% PV scenario c) Voltage profile 70% PV scenario d) Voltage fluctuations 70% PV scenario e) Voltage profile 100% PV scenario f) Voltage fluctuations 100% PV scenario

Figure 13 shows the $|\Delta V|$ values for the 2000 most heavily fluctuating time steps in each scenario and the current situation for Line 6. In Figure 13, the fluctuations are sorted by severity. Similarly to Figure 11, Figure 13 shows the thresholds for visible and annoying voltage flicker. Comparing the current situation with the PV penetration scenarios shows that the magnitude of voltage fluctuations has increased greatly with an increasing solar PV capacity.

From Figure 13 it can be observed that the voltage flicker thresholds are crossed. For the 40% PV scenario, only the visible voltage flicker threshold is crossed. In Line 6, the maximum observed fluctuation is $1.634V$ and the threshold is crossed 0.96% of all time steps between sunset and sundown on 4 August 2017. In the 70% PV scenario, both the visible and annoying flicker thresholds are crossed. For Line 6, the maximum voltage fluctuation is $3.063V$, which is significantly larger compared to the 40% scenario. In the 70% scenario, the Annoying flicker threshold is crossed 0,37% of the time, whereas the Visible flicker threshold is crossed 4.26% of the time. The 100% PV scenario experiences the most heavy voltage fluctuations. The maximum voltage fluctuation reaches up to $4{,}362V$, which is more than double the annoying flicker threshold. The annoying flicker is present 1,27% of the time, and it is visible 7,37% of the measured time steps, which is very significant. All in all, Figure 13 shows that problems because of voltage flicker are expected with an increasing PV penetration rate.

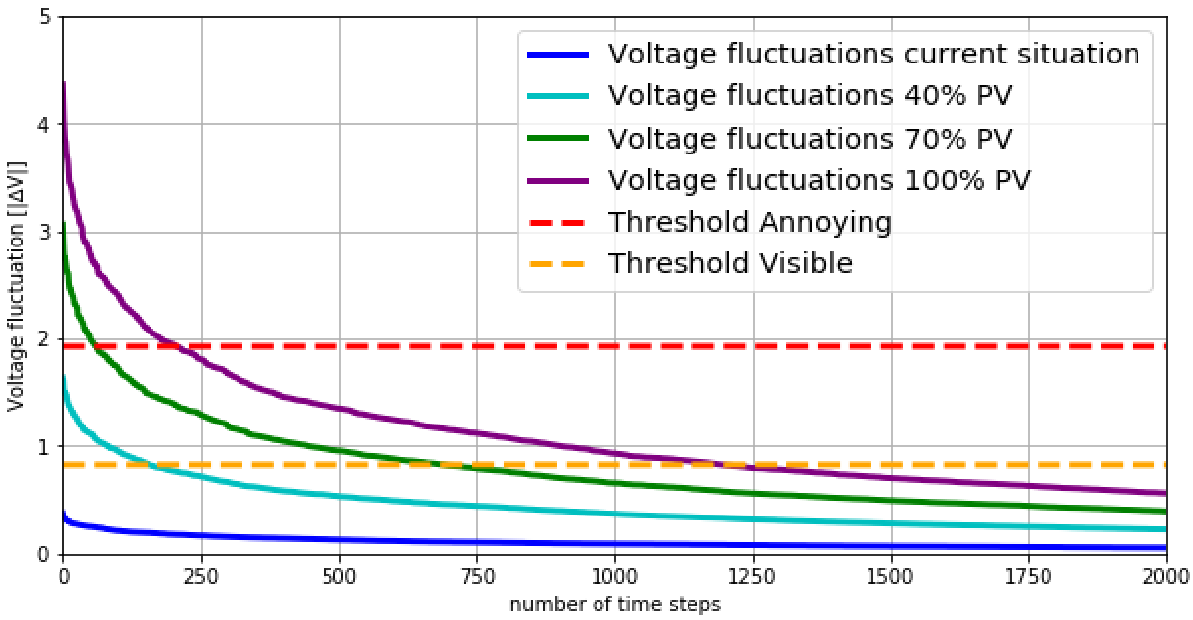

Figure 13: Voltage fluctuations current situation and PV penetration scenarios sorted by magnitude

The results for all the different analyzed lines can be seen in Table 3. The left values represent the percentage of time that the visible voltage flicker threshold was crossed, the right values represent the percentage of time that the Annoying flicker threshold was crossed. Table 3 shows that in each scenario, visible flicker is present in all lines. However, the extent to which the flicker is present varies for the different lines. For the 40% scenario, visible flicker in the different lines varies between 0.09% and 0.96%, for the 70% scenario this is between 1.38% and 4.26% and for the 100% scenario this is between 3.47% and 7.37%. The annoying flicker vary between 0% and 0.37% in the 70% scenario and between 0.14% and 1.27% in the 100% scenario. These values show that the extent of the voltage flicker problem differs quite significantly between the different lines, but that the voltage flicker problem is present throughout the entire Lombok LV grid. Hence, it can be stated that voltage flicker is expected to be a problem in the LV grid once the PV penetration rate increases.

Table 3: Flicker occurrence per line

	Visible Flicker: $\|\Delta V\| \geq \mathbf{0.826V}$			**Annoying Flicker: $\|\Delta V\| \geq \mathbf{1.927V}$**		
Scenario	*40%*	*70%*	*100%*	*40%*	*70%*	*100%*
Line 1	0.09%	1.38%	3.47%	0%	0.01%	0.14%
Line 2	0.10%	1.53%	3.80%	0%	0.01%	0.17%
Line 3	0.46%	2.77%	5.44%	0%	0.16%	0.65%
Line 4	0.84%	3.93%	7.06%	0%	0.30%	1.10%
Line 5	0.69%	3.26%	5.97%	0%	0.21%	0.79%
Line 6	0.96%	4.26%	7.37%	0%	0.37%	1.27%
Line 7	0.30%	1.71%	3.48%	0%	0%	0.09%
Line 8	0.67%	2.36%	4.31%	0%	0.01%	0.19%
Line 9	0.75%	2.67%	4.64%	0%	0.02%	0.23%
Line 10	0.21%	1.84%	3.92%	0%	0.03%	0.29%
Line 11	0.74%	2.66%	4.62%	0%	0.01%	0.22%
Transformer	0%	0.04%	0.24%	0%	0%	0%

Figure 14 shows the voltage profiles of all the lines for the 100% PV scenario, zoomed in to show 13.00 until 14.00. This figure can be used to compare the voltages among the different types of line as described in Table 2. Since the lines differ with regard to type, location in the grid, place in the cable, and loading, each of these aspects is discussed separately.

As described in Table 2, Line 1 and Line 2 represent the effect of the type of line on the voltage fluctuations present. Line 2 has a higher resistance compared to Line 1 because the cable becomes more narrow at this point. Figure 14a shows that the more narrow line has slightly higher peaks in voltage. This results in slightly more flicker, as can also be seen in Table 3. This supports the statement that grid reinforcement can help to reduce voltage flicker in the LV grid, but the extent to which it can help remains unclear. This observation can be supported by Figure 14c, which compares Line 5 and Line 6. These lines represent the beginning and end of the most narrow cable present in the grid, this cable has the highest resistance of all cable types in the Lombok LV grid and is therefore more likely to experience larger voltage fluctuations. Figure 14c and the results in Table 3 show that Line 6 is the line which experiences the most heavy voltage fluctuations. This confirms that voltage fluctuations are affected by the cable type.

The effect of the place within the grid on a cable on voltage fluctuations is illustrated by Line 3 and Line 4 in Figure 14b. Both show relatively large voltage fluctuations, even though Line 3 is a measurement at the beginning of a cable this line still has larger voltage fluctuations than for instance Line 2, which is the same cable type and at past the middle of the cable. This can be explained by the place of Line 3 in the Lombok LV grid. Figure 4 shows that the cable of Line 3 is not directly connected to the transformer. This confirms the suspicion that the further a cable is away from the transformer, the larger the voltage fluctuations. This reasoning also holds for Line 5, which is also at the beginning of a cable, but the cable is not directly connected to the transformer.

The effect of the place on a cable on voltage fluctuations is best shown by Figure 14d, which shows the voltage fluctuations on three different places on the same cable. Supported by Table 3, Figure 14d shows that the further up a cable, the larger the voltage fluctuations are. This effect is supported by Figure 14b and Figure 14c, which both show the difference between a measurement at the beginning and at the end of a cable. In both cases, the voltage fluctuations at the end of a cable are much more prominent than at the beginning of the same cable.

As described in Table 2, Line 10 and Line 11 show the effect of loading on a relatively wide 70mm-cable. Line 10 has much less loading attached because of fewer household grid connections and because much less roofs which are suitable for solar PV systems. Even though Line 11 has the same cable type as Line 10, Line 11 experiences much more loading. The effect of the loading on voltage fluctuations can be observed in Figure 14 and Table 3. Both conclude that the larger the loading on a cable, the larger the voltage fluctuations in the cable.

The voltage profile at the transformer shows that the transformer experiences way lower voltage fluctuations compared to all cables. This is most likely due to that the busbar is built to handle much more load to go through. Unless stated otherwise, further analysis focuses solely on Line 6 because this line experiences the largest voltage fluctuations. When the voltage fluctuation mitigation options are able to mitigate voltage flicker at Line 6, it can be assumed that this option is able to mitigate voltage fluctuations throughout the entire analyzed grid.

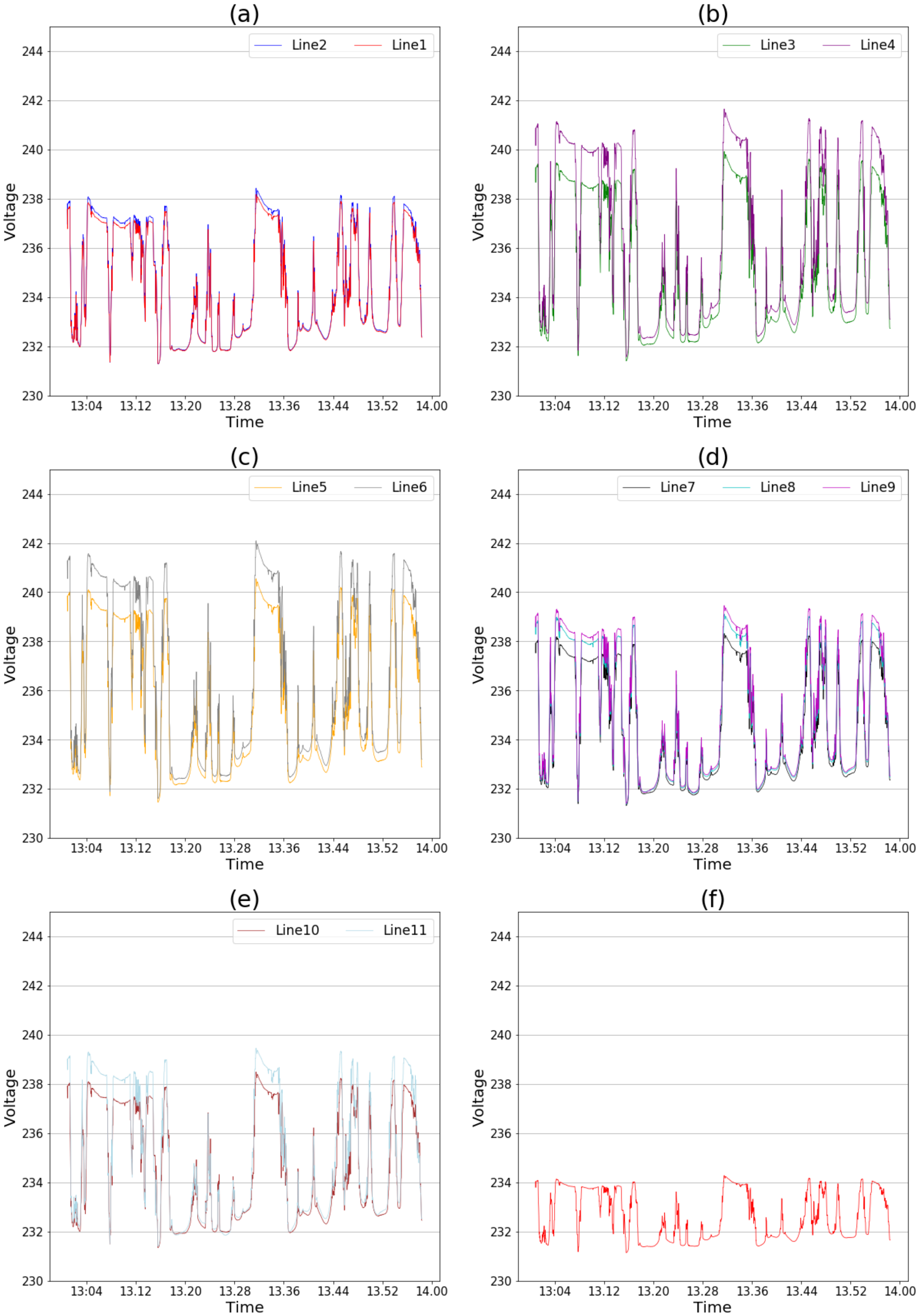

Figure 14: a) Voltage profiles Line 1 and Line 2 b) Voltage profiles Line 3 and Line 4 c) Voltage profiles Line 5 and Line 6 d) Voltage profiles Line 7, Line 8 and Line 9 e) Voltage profiles Line 10 and Line 11 f) Voltage profile Transformer

6.3. Exploring possible solutions

This section shows the voltage flicker results for each of the three different voltage fluctuation mitigation options for each of the scenarios separately. The results are compared to the scenario results from Section 6.2. in order to assess the suitability of the different options to reduce voltage flicker. Firstly, the active power curtailment option is discussed, next the grid reinforcement option and lastly the supercapacitor option is elaborated upon. Finally, the results in this section are afterwards used to compare the different voltage fluctuation mitigation options (Section 6.4.).

6.3.1. Option 1: Active power curtailment

As described in Section 4.3.1., the results for active power curtailment were generated using five iterations per scenario. The choice to do five iterations in each scenario has been made because of limited time and computing power. The reason to use iterations is that the PowerFactory software was not able to predict changes in voltage profiles because of curtailment and to act on those changes. Therefore, based on each new voltage profile a new curtailment strategy had to be determined, this was done five separate times for each scenario.

Figure 15 shows the voltage flicker results for the 2000 most heavily fluctuating time steps in the 40% PV scenario. The black line shows the results without interference. Figure 15 seems to show that for the 500 most heavily fluctuating time steps, the active power curtailment lines are below the black line. This indicates that active power curtailment reduces the voltage flicker. However, when we zoom in on the fifteen most fluctuating time steps (Figure 16), we can see that the maximum voltage fluctuations are larger in the situations with active power curtailment than in the situation without curtailment. This furthermore results in all five iterations experiencing annoying flicker, whereas the no interference situation does not experience annoying flicker. This can be explained by the methodology for curtailment, the PV profiles were curtailed based on the voltage profile of Line 6. However, not all PV profiles in the LV grid are equal. Therefore, it is possible that at certain places in the LV grid, PV was curtailed a few seconds too early or too late, which results in even larger drops or rises in power production at these locations. Even if this happens at another part of the analyzed LV grid, this still has effect on the voltage at Line 6, since all cables in the analyzed LV grid are interlinked. Possible solutions for this problem are discussed in Section 7.3.

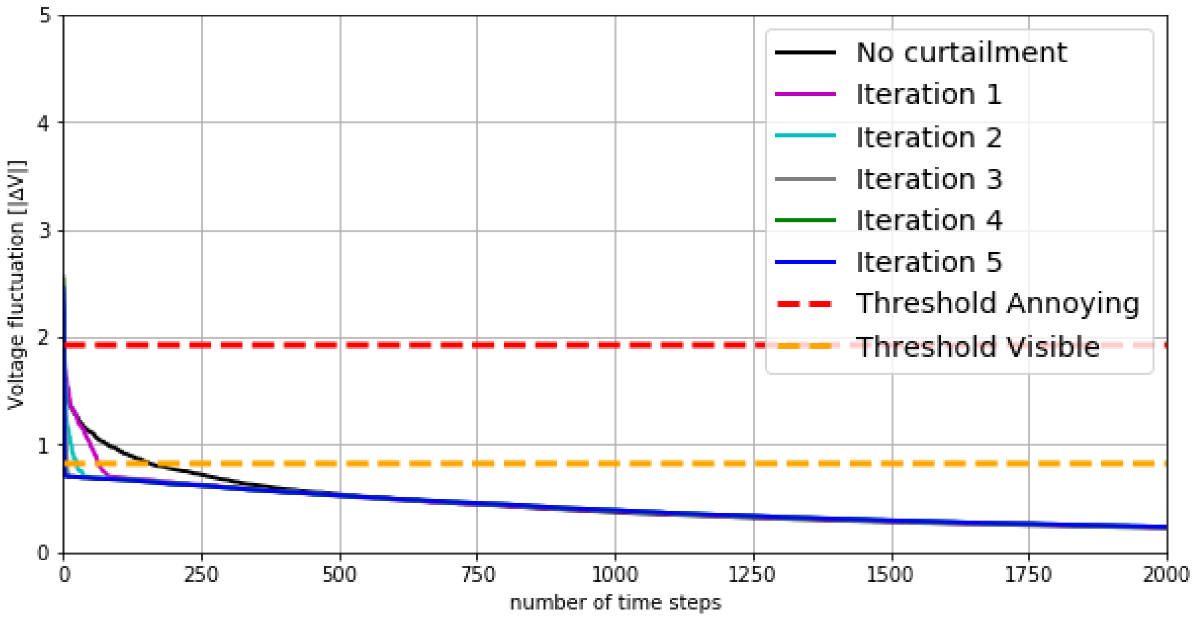

Figure 15: Voltage fluctuations 40% PV and curtailment sorted by magnitude – 2000 most fluctuating time steps

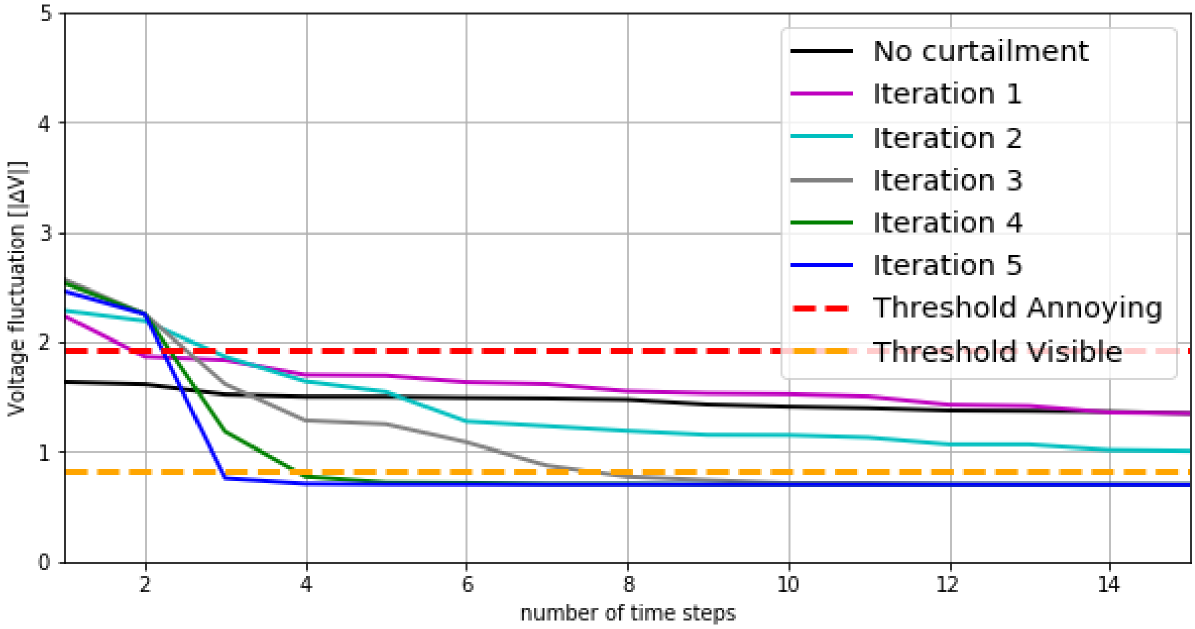

Figure 16: Voltage fluctuations 40% PV and curtailment sorted by magnitude – 15 most fluctuating time steps

Table 4 summarizes the results for all time steps analyzed in this scenario. Besides the occurrence of voltage flicker for each iteration, Table 4 furthermore shows the total amount of active power that was curtailed. Table 4 shows that the visible voltage flicker was reduced very significantly. It was reduced by 98.7%, which was reached by curtailing only 0.51% of the PV power produced. Since the same curtailment profile was used throughout the entire analyzed grid, this 0.51% curtailment applies to all solar PV systems. However, the annoying flicker increased by doing so. Even though this analysis has shown the difficulty of curtailing the active power at the right time, it can be concluded that active power curtailment is a promising option to reduce voltage flicker in the 40% PV scenario.

Table 4: Flicker occurrence 40% PV and curtailment

40% PV	**Flicker**		**Cumulative curtailed [%]**	**Largest fluctuation [$|\Delta V|$]**
	Visible [%]	Annoying [%]		
No curtailment	0.96	0	-	1.634
Iteration 1	0.38	0.01	0.31	2.236
Iteration 2	0.15	0.01	0.44	2.286
Iteration 3	0.04	0.01	0.48	2.569
Iteration 4	0.02	0.01	0.50	2.536
Iteration 5	0.01	0.01	0.51	2.463

Figure 17 shows the voltage flicker results for the 2000 most heavily fluctuating time steps in the 70% PV scenario, Figure 18 zooms in on the 25 most fluctuating time steps. The figures show similar behavior to the 40% PV scenario. In this scenario, the largest voltage fluctuations are larger than those in the no curtailment scenario. However, they do become smaller quite quickly. The reason that they start higher is similar as explained in the 40% scenario. The biggest difference is that the effect of the different iterations becomes visible more clearly. Figure 18 furthermore shows that there is no significant improvement between the fourth and fifth iteration. This suggests that these iterations show the maximum voltage flicker mitigation in the 70% PV scenario using this method. This does not exclude the possibility of more voltage flicker mitigation using other methods.

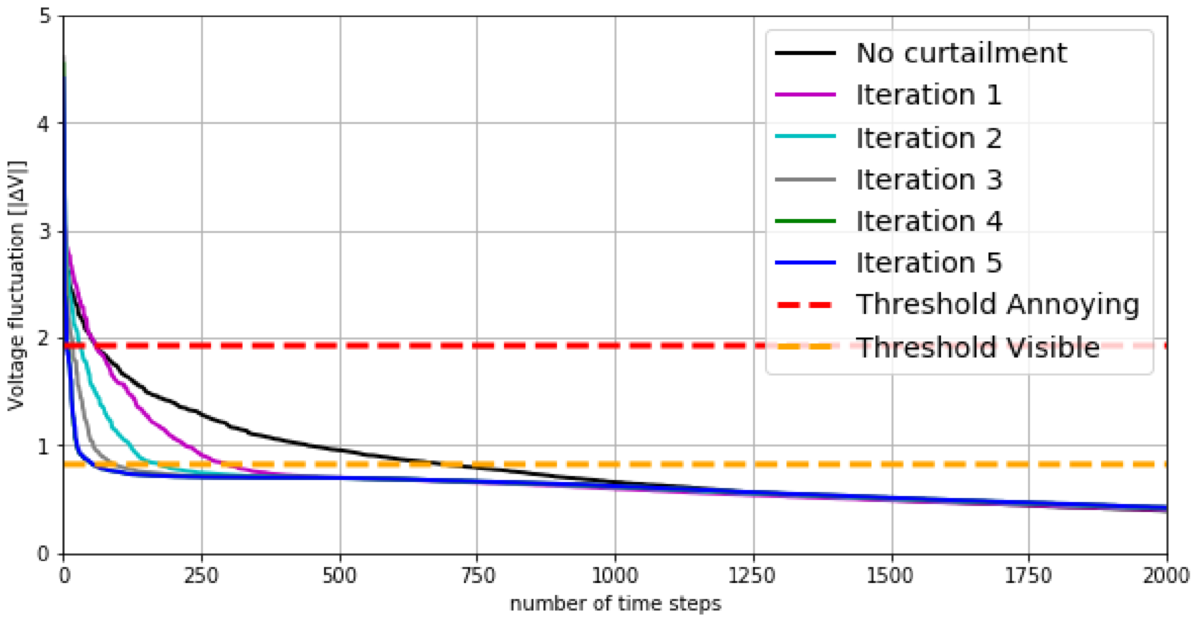

Figure 17: Voltage fluctuations 70% PV and curtailment sorted by magnitude – 2000 most fluctuating time steps

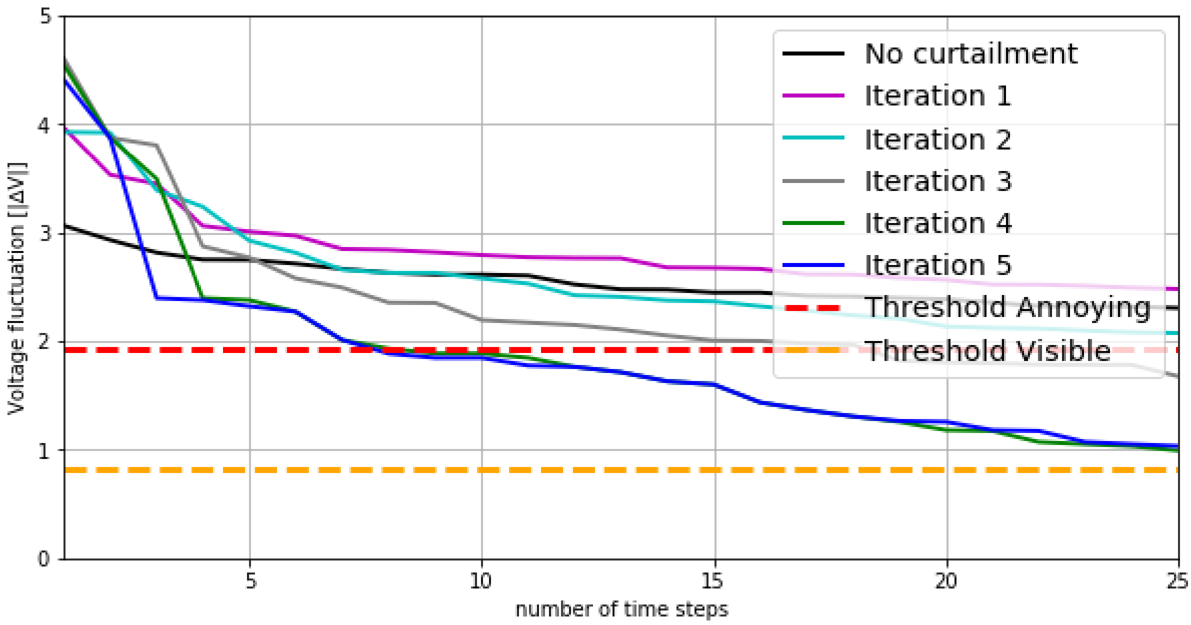

Figure 18: Voltage fluctuations 70% PV and curtailment sorted by magnitude – 25 most fluctuating time steps

Table 5 summarizes the results for all time steps analyzed in this scenario. It shows that the visible flicker was significantly reduced by 92.3%, requiring 1.45% of the PV power output to be curtailed. The annoying flicker was reduced by 88.3%. This means that the reduction of visible flicker is much lower than in the 40% PV scenario. The reduction of annoying flicker cannot be compared between the 40% and 70% scenarios because the 40% scenario initially did not experience annoying flicker. Moreover, extra PV power output has to be curtailed in order to reach this goal. 1.45% percent has to be curtailed in the 70% scenario, whereas 0.51% was curtailed in the 40% scenario, this is an increase of 184%. All in all, active power curtailment can still be seen as a promising option to counter voltage flicker in the 70% PV scenario, but this method does not solve the problem entirely.

Table 5: Flicker occurrence 70% PV and curtailment

70% PV	**Flicker**		**Cumulative curtailed [%]**	**Largest fluctuation [$\|\Delta V\|$]**
	Visible [%]	Annoying [%]		
No curtailment	4.26	0.37	-	3.063
Iteration 1	1.83	0.36	0.78	3.970
Iteration 2	1.07	0.19	1.13	3.927
Iteration 3	0.56	0.11	1.33	4.609
Iteration 4	0.32	0.05	1.44	4.547
Iteration 5	0.33	0.04	1.45	4.412

Figure 19 shows the voltage flicker results for the 2000 most heavily fluctuating time steps in the 100% PV scenario Figure 20 zooms in on the 40 most fluctuating time steps. Again, the figures show similar behavior compared to the 70% and 40% PV scenarios, but the voltage fluctuations are larger. One difference between the 100% PV scenario and the 70% PV scenario is that in this case, there is a serious difference between the fourth and fifth iteration. This indicates that another iteration might improve the results. The figures furthermore show that the largest voltage fluctuation is more than three times the size of the annoying voltage flicker threshold, which is very undesirable in the LV grid.

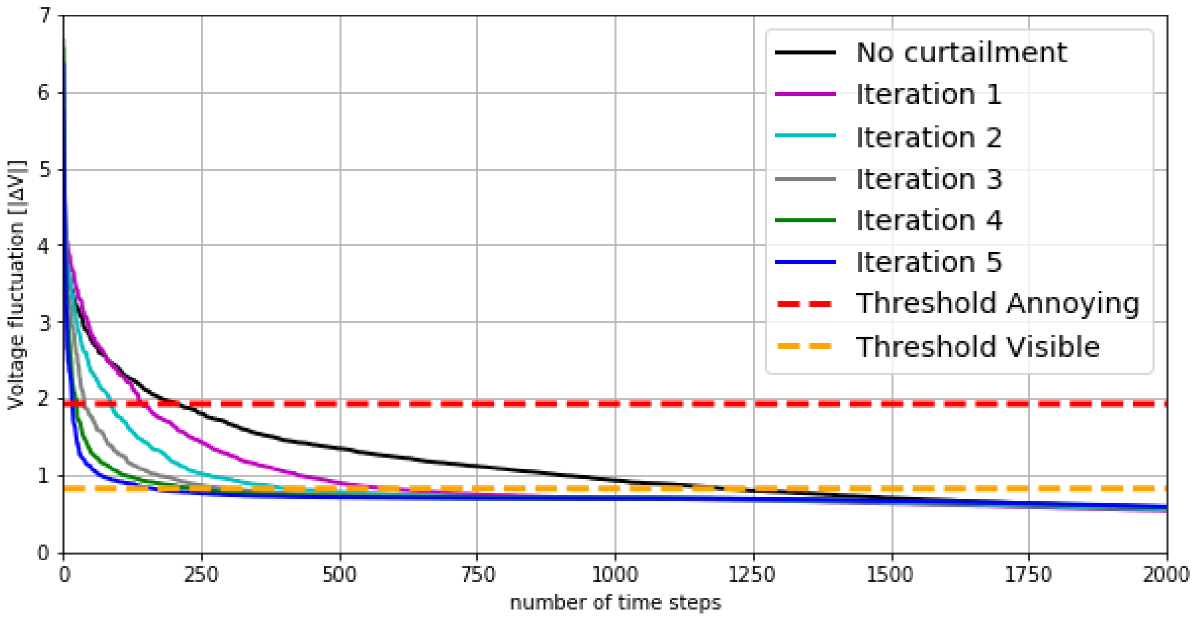

Figure 19: Voltage fluctuations 100% PV and curtailment sorted by magnitude – 2000 most fluctuating time steps

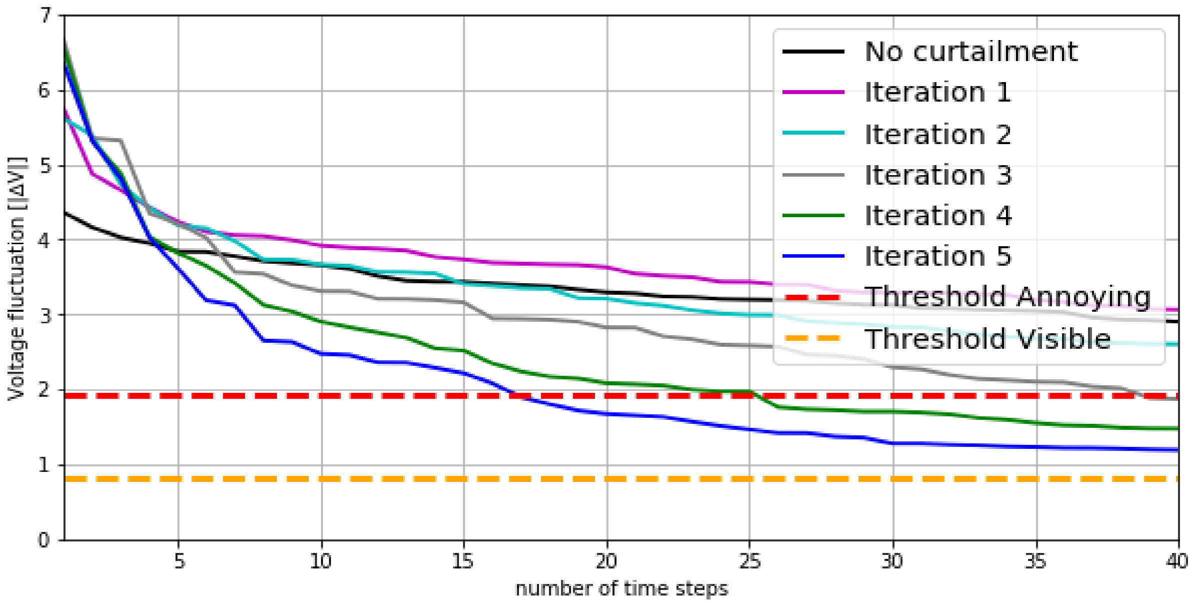

Figure 20: Voltage fluctuations 100% PV and curtailment sorted by magnitude – 40 most fluctuating time steps

Table 6 summarizes the results for all time steps analyzed in this scenario. It shows that the visible flicker was significantly reduced by 86.3%, requiring 2.26% of the PV power output to be curtailed, this is 56% more than in the 70% scenario and 334% more than in the 40% scenario. The annoying flicker was reduced by 91.8%. These results show that it becomes increasingly hard for active power curtailment to reduce voltage flicker, the larger the PV penetration rate in the LV grid, the more PV power has to be curtailed. Furthermore, more voltage flicker remains, the larger the PV penetration rate. Given the fact that there is still visible voltage flicker at more than 1% of the time steps in this 100% PV scenario, it can be concluded that curtailment alone is not sufficient for voltage flicker mitigation using the methodoloy applied in this thesis. However, this does not exclude the possibility for it to be effective using another method that curtails active power at the right place at the right time more precisely.

Table 6: Flicker occurrence 100% PV and curtailment

100% PV	**Flicker**		**Cumulative curtailed [%]**	**Largest fluctuation [$\|\Delta V\|$]**
	Visible [%]	Annoying [%]		
No curtailment	7.37	1.27	-	4.362
Iteration 1	3.59	0.88	1.08	5.747
Iteration 2	2.50	0.52	1.61	5.611
Iteration 3	1.80	0.23	1.94	6.667
Iteration 4	1.46	0.15	2.13	6.553
Iteration 5	1.01	0.10	2.26	6.350

Figure 21 shows the effect of active power curtailment on the voltage fluctuation profile in the 100% PV scenario. Figure 21a is a selection of the voltage fluctuation profile without interference (Figure 12f) and Figure 21b is the same voltage profile after curtailment has been applied. Figures 21a and 21b furthermore show the thresholds for visible and annoying voltage flicker. In Figure 21 it can be seen that these thresholds are crossed often without interference, but that in the situation with curtailment, the thresholds are crossed much less often.

Figure 21 clearly shows the purpose of the active power curtailment strategy, namely to only curtail power when the voltage fluctuations cross a certain thresholds, in this case 0.70V. This results in that the profile between the visible threshold lines remains more or less equal in both figures., but that the rest of the profile changes radically. In most cases, this has resulted in lower voltage fluctuations, but in some cases the voltage fluctuations have increased, for instance around 11:12. This illustrates the aforementioned problem with this methodology, which causes the curtailment happening a few seconds too late or a few seconds too early in other parts of the LV grid.

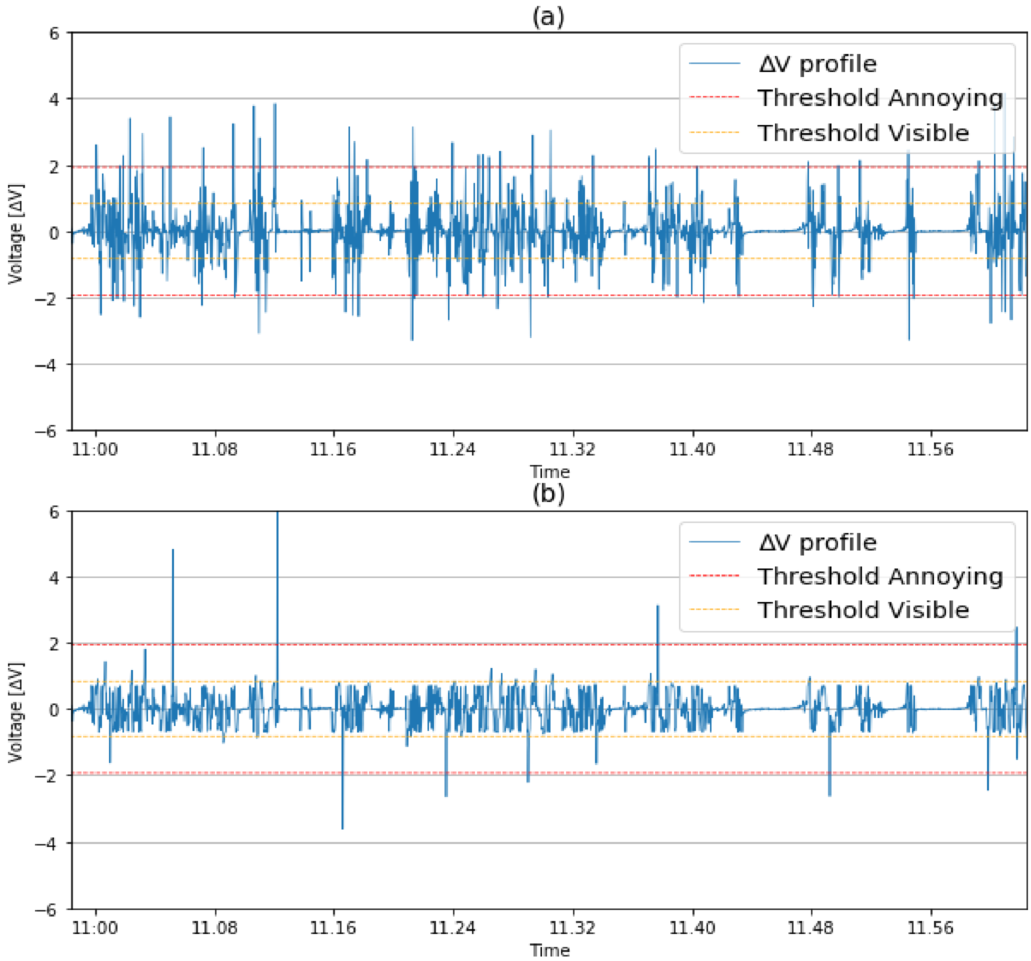

Figure 21: a) Voltage fluctuations 100% PV scenario 11:00-12.00 – no interference b) Voltage fluctuations 100% PV scenario 11:00-12.00 – curtailed

6.3.2. Option 2: Grid reinforcement

As described in Section 4.3.2., this voltage fluctuation mitigation option replaces all cables present in the analyzed LV grid with 4x150mm VVMvKhas/Alk 4x6 cables in order to lower the resistance in the cables, thus mitigating large voltage fluctuations. This option shows the maximum potential effect of grid reinforcement on voltage fluctuations because the 4x150mm VVMvKhas/Alk 4x6 cable is the cable with the lowest resistance which is commonly used in the LV grid. In reality, it is not economically feasible to change all cables in all parts of the LV grid (Von Appen et al., 2013). However, is does provide interesting insights in whether it is a serious option to consider at certain specific locations.

Figure 22 shows the results for all of the scenarios, comparing the voltage flicker for the scenarios with and without grid reinforcement. The figure shows similar behavior in each of the scenarios. The reinforced voltage profile simply seems to be a fraction of the original profile. This results in the values presented in Table 7. This table shows that in the 40% PV scenario, it is still possible for grid reinforcement to counter a large part (78.21%) of the visible voltage flicker. In the 70% PV scenario this becomes harder and only 58.12% of the visible flicker was mitigated. In the 100% PV scenario not even half (47.57%) of the visible voltage flicker was mitigated. Grid reinforcement does a better job in mitigating annoying voltage flicker, however it still remains present 0.02% of the time in the 70% scenario and 0.26% of the time in the 100% PV scenario. Given these results, it can be concluded that even with maximum grid reinforcement, voltage flicker in the LV grid cannot be mitigated when PV penetration rates rise.

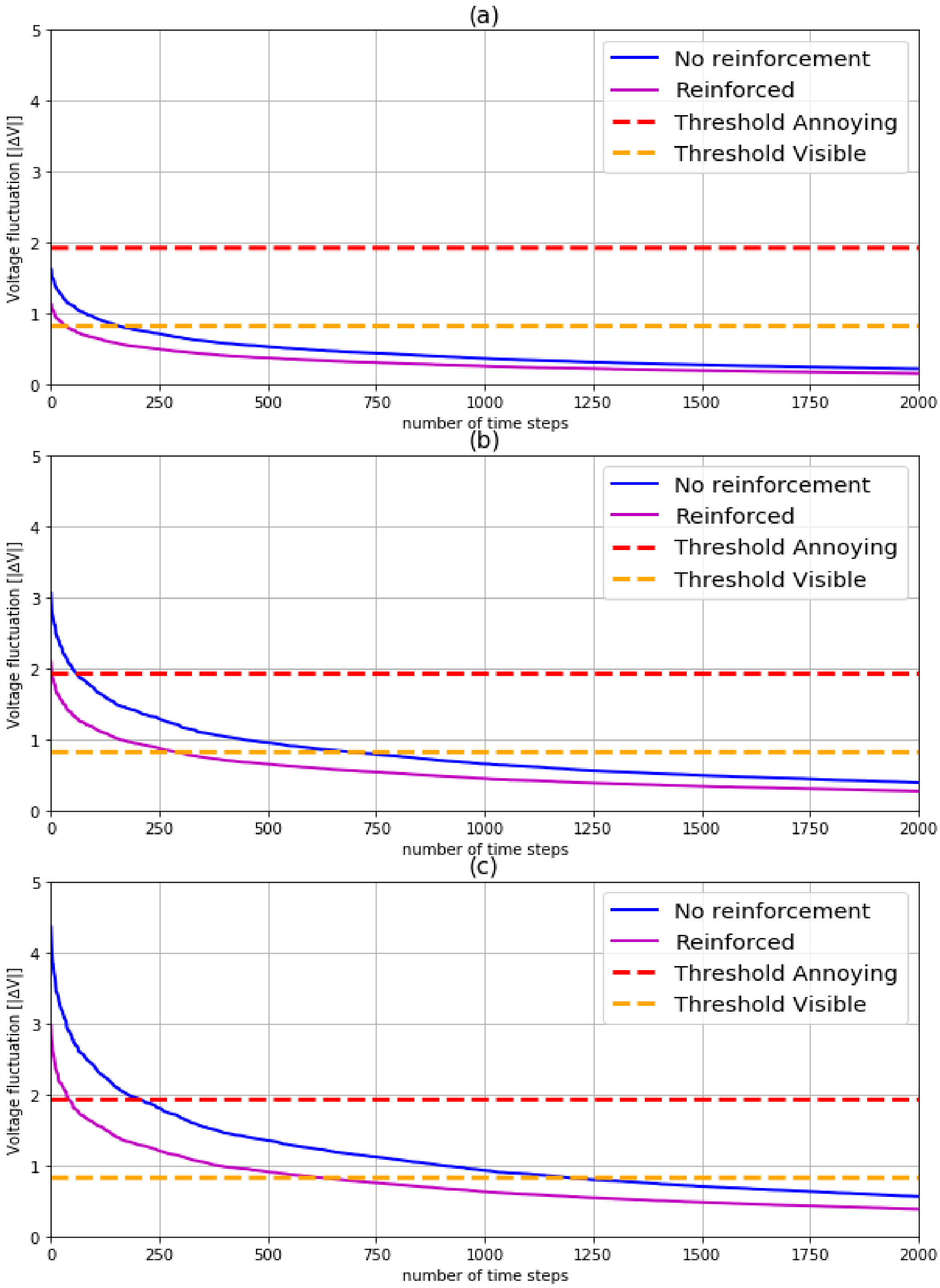

Figure 22: a) Voltage fluctuations in the 40% PV scenario with and without reinforcement – sorted by magnitude b) Voltage fluctuations in the 70% PV scenario with and without reinforcement – sorted by magnitude c) Voltage fluctuations in the 100% PV scenario with and without reinforcement – sorted by magnitude

Table 7: Flicker occurrence with and without grid reinforcement

	Visible flicker			**Annoying flicker**		
	Not reinforced [%]	Reinforced [%]	*Flicker reduced [%]*	Not reinforced [%]	Reinforced [%]	*Flicker reduced [%]*
40% PV	0.96	0.21	*78.21*	0	0	-
70% PV	4.26	1.78	*58.12*	0.37	0.02	*95.00*
100% PV	7.37	3.86	*47.57*	1.27	0.26	*79.61*

The effect of grid reinforcement on voltage fluctuations differs significantly per line analyzed. This is because of large differences in resistance in the different cables in the Lombok LV grid, the larger the reduction in resistance, the larger the effect of grid reinforcement. Appendix B aims to show this effect.

Figure 23 shows the effect of grid reinforcement on the voltage fluctuation profile in the 100% PV scenario. Figure 23a is a selection of the voltage fluctuation profile without interference (Figure 12f) and Figure 23b is the same voltage profile after grid reinforcement has been applied. Figure 23 supports the suspicion that grid reinforcement merely results in the new voltage fluctuation profile to be a less fluctuating version of the initial profile. Figure 23b shows the same behavior as Figure 23a, all the peaks are just smaller which results in fewer voltage fluctuations being present. This explains that the grid reinforcement option has more promising results the lower the PV penetration rate, since it is easier to mitigate smaller fluctuations.

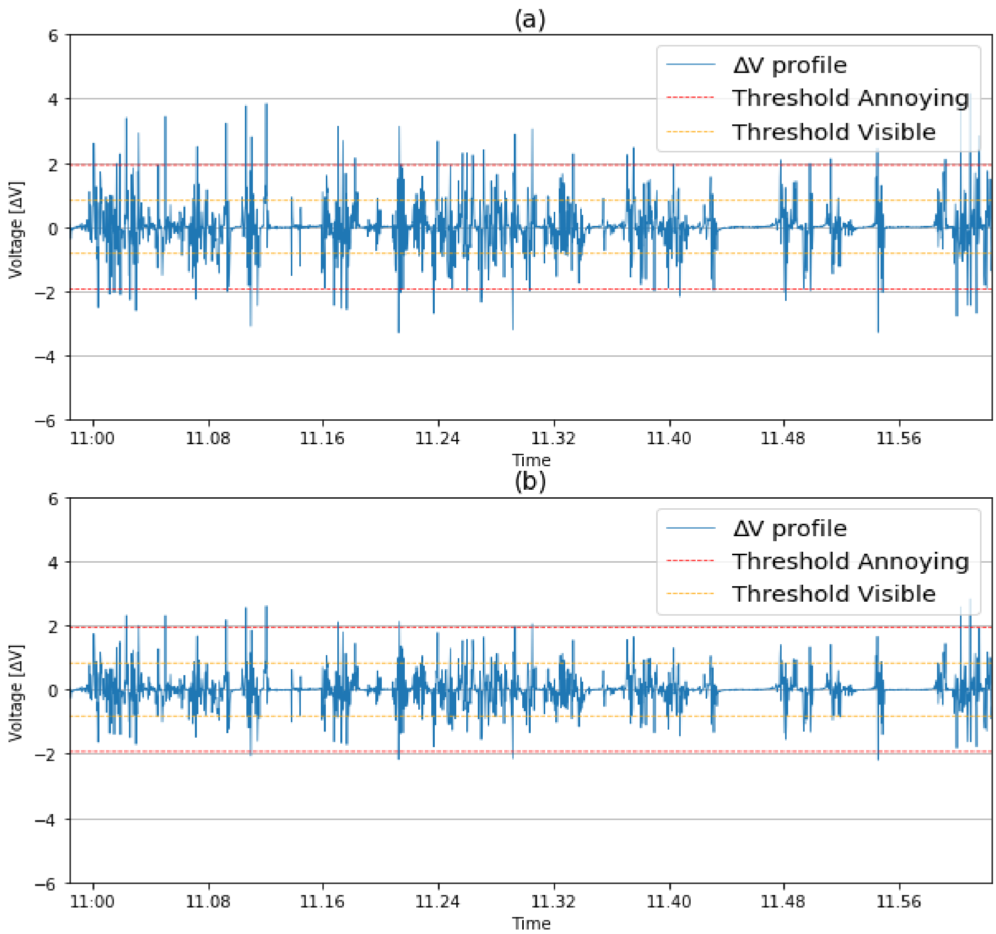

Figure 23: a) Voltage fluctuations 100% PV scenario 11:00-12.00 – no interference b) Voltage fluctuations 100% PV scenario 11:00-12.00 – reinforced

6.3.3. Option 3: Supercapacitor

As described in Section 4.3.3., for this option, a supercapacitor was added to each PV system. The supercapacitor was modeled in such a way that its output is a moving average of the attached PV profile. 6-, 10- and 20-second moving averages were generated for each scenario, so that it can be assessed what should be the requirements for supercapacitors if applied to PV systems. Based on the results, the required supercapacitor sizes and ramp rates were determined. With this information, it can be assessed what size of supercapacitor would be desirable to mitigate voltage fluctuation.

Figure 24 and Table 8 show the results for the supercapacitor option. Figure 24 shows that each of the scenarios shows similar results. In the 40% PV scenario, both Figure 24a and Table 8 show that a 6-second moving average is sufficient to reduce almost all voltage flicker. Merely 0.02% of the time steps show visible voltage flicker using a 6-second moving average in the 40% PV scenario, which is much less compared to 0.96% of the time steps without a supercapacitor. Since a relatively short moving average of 6 seconds is almost sufficient, it is logical that using a longer moving average (10 or 20 seconds) results in no visible voltage flicker being left. This is because the peaks in voltage are divided over more time steps and will thus be less strong. Since no annoying flicker was present in the 40% PV scenario, this is also not the case when using the moving averages.

Contrary to the 40% PV scenario, in the 70% PV scenario there is annoying voltage flicker present. Figure 24b and Table 8 show that using any of the moving averages result in 100% reduction in annoying voltage flicker. However, with the 6-second moving average, still a significant amount of visible voltage flicker remains (1.06% of time steps with supercapacitor compared to 4.26% without supercapacitor. Using the 10-second moving average in the 70% PV scenario results in the mitigation of almost all voltage flicker, just 0.19% remains. A 20-second moving average would mitigate all voltage flicker in 70% PV scenario. Also in the 70% scenario, all annoying voltage flicker was mitigated by using any of the moving averages.

In the 100% PV scenario this is not the case. There is still annoying voltage flicker (0.04% of the time steps) present in the 100% PV scenario when using a 6-second moving average. Using a 10-second moving average in this scenario mitigates all annoying voltage flicker, but it still leaves visible flicker at 1.66% of the time steps, which is quite significant. In the 100% PV scenario, the visible flicker can be further mitigated until only 0.09% remains using a 20-second moving average. Hence, it can be deduced that a 20-second moving average would be sufficient for voltage flicker mitigation in almost all circumstances.

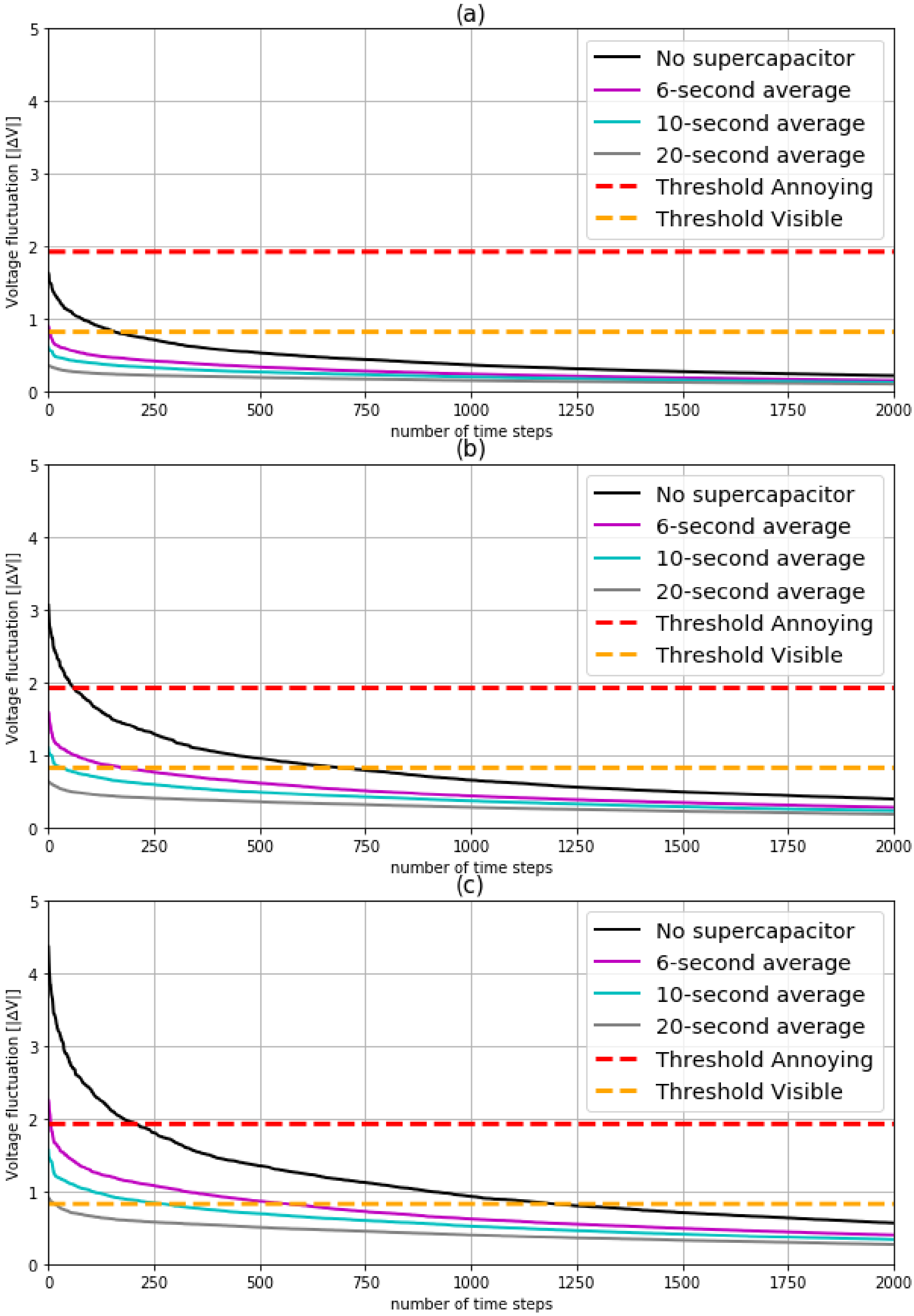

Figure 24: a) Voltage fluctuations in the 40% PV scenario with and without supercapacitor – sorted by magnitude b) Voltage fluctuations in the 70% PV scenario with and without supercapacitor – sorted by magnitude c) Voltage fluctuations in the 100% PV scenario with and without supercapacitor – sorted by magnitude

Table 8: Flicker occurrence using a supercapacitor

	Flicker		***Flicker reduced***	
	Visible [%]	Annoying [%]	*Visible [%]*	*Annoying [%]*
		40%		
No Capacitor	0.96	0	-	-
6-seconds	0.02	0	*98.08*	-
10-seconds	0	0	*100.0*	-
20-seconds	0	0	*100.0*	-
		70%		
No Capacitor	4.26	0.37	-	-
6-seconds	1.06	0	*75.22*	*100.0*
10-seconds	0.19	0	*95.51*	*100.0*
20-seconds	0	0	*100.0*	*100.0*
		100%		
No Capacitor	7.37	1.27	-	-
6-seconds	3.48	0.04	*52.76*	*97.09*
10-seconds	1.66	0	*77.47*	*100.0*
20-seconds	0.09	0	*98.83*	*100.0*

Figure 25 shows the effect of the 20-second supercapacitor on the voltage fluctuation profile in the 100% PV scenario. Figure 25a is a selection of the voltage fluctuation profile without interference (Figure 12f) and Figure 25b is the same voltage profile after the supercapacitor has been applied. The voltage fluctuation profile of Figure 25b differs very significantly from the voltage fluctuation profile from Figure 25a. This is a result from using moving averages. The moving average results in the peaks to be divided over different time steps which result in lower peaks after using the supercapacitor. Figure 25b show that because of the supercapacitor, all annoying flicker and almost all visible flicker was mitigated. Figure 25b supports the aforementioned statement that a supercapacitor is a very suitable option for voltage flicker mitigation.

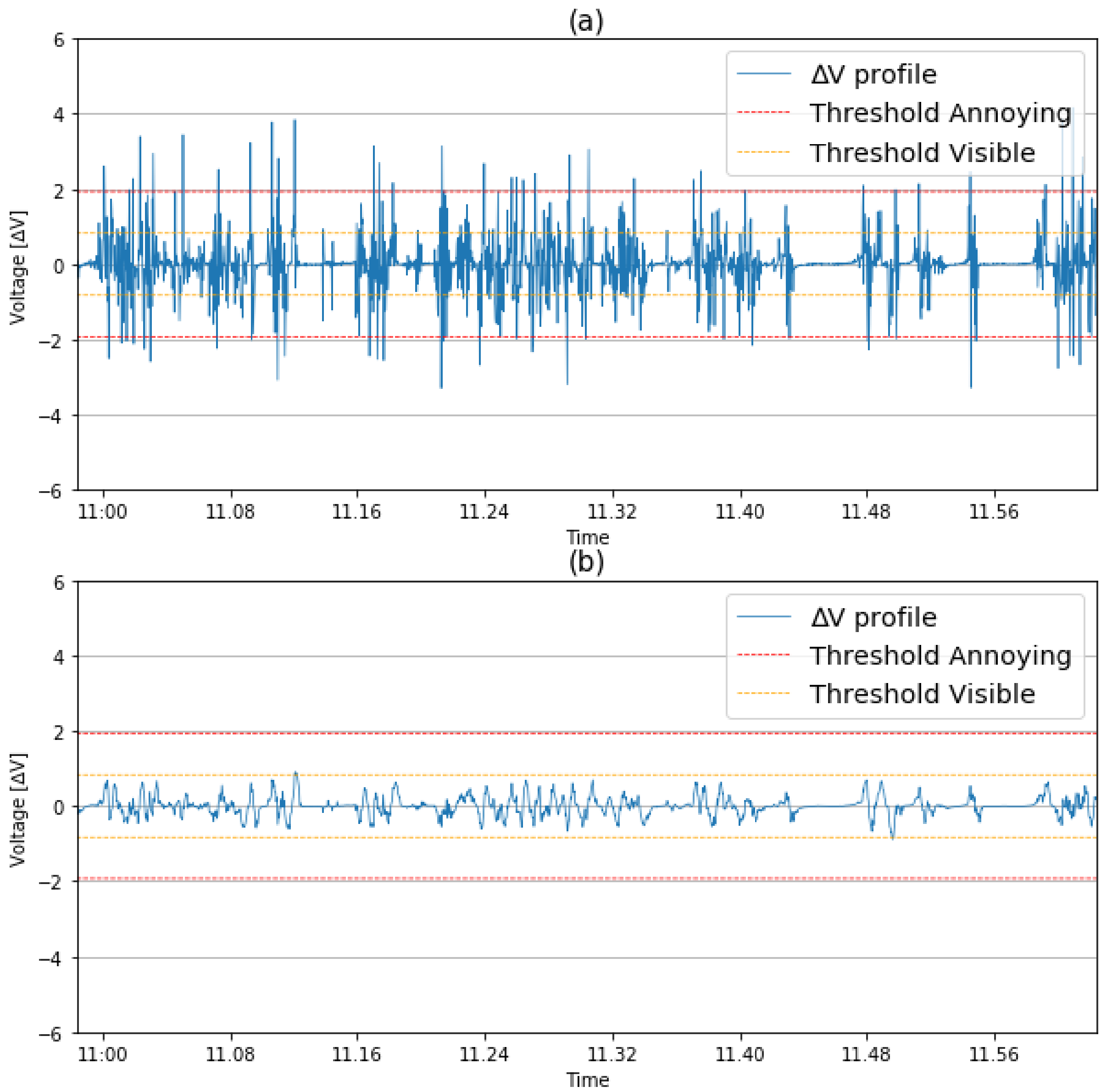

Figure 25: a) Voltage fluctuations 100% PV scenario 11:00-12.00 – no interference b) Voltage fluctuations 100% PV scenario 11:00-12.00 – supercapacitor

In order to be able to apply the supercapacitor, one should know what the requirements for the supercapacitor are. Table 9 shows the requirements for required size and required ramp rate for each of the different supercapacitor types. The requirements were determined according to the method described in Section 4.3.3. The results are presented relatively to the solar PV system size. The requirements presented are the requirements corresponding to the initial PV profiles that were used to generate all individual profiles. The reason to choose these profiles is that these are the only ones with actual measurements and are therefore the most realistic. The results in Table 9 show that the larger time the moving average covers, the larger the supercapacitor size and ramp rates required. For an average PV system of 3.6 kWp, the supercapacitor would have to be able to store 4.97 Wh and it would need to be able to ramp a maximum of 5.40 kW if it needs to handle a moving average of 20 seconds. Since supercapacitors have a typical specific energy of 5 Wh/kg and a Specific power of up to 10 kW/kg (Maxwell Technologies, 2009), a 1kg supercapacitor could be enough to meet this demand. What furthermore stands out from Table 9 is that the requirements for the ramp rate increases more sharply than the required capacitor size does when the moving average time increases. However, since the specific power of a supercapacitor is generally relatively larger than its specific energy, this should not have an effect on the required supercapacitor.

Table 9: Requirements for supercapacitors

	Supercapacitor size required [Wh/kWp]	**Supercapacitor required ramp rate [kW/kWp]**
6-seconds	1.04	0.87
10-seconds	1.24	1.23
20-seconds	1.38	1.50

Supercapacitors do experience power losses. The power losses in supercapacitors are mainly caused by the resistance within the capacitor, but are also effected by frequency, temperature and current. Since every individual PV system would require a different size of supercapacitor because of the different sizes of the PV systems and because the requirements could be met by using different types of supercapacitor, it is hard to precisely determine the power losses that the average PV system would experience when using a supercapacitor. Maxwell Technologies (2009) state that for most uses, supercapacitors have efficiencies in excess of 98%. Gekakis et al. (2015) tested the efficiency of different types of supercapacitor at different power values. They conclude that in ideal circumstances, supercapacitors can reach an efficiency of close to 100%. They conclude that it can be safely stated that the efficiency of a supercapacitor is 95% or higher when the performance of the supercapacitor is not jeopardized by non-ideal operation. An example of non-ideal operation is a too large or too low operating voltage for the desired power flow. Therefore, we can conclude that the use of a supercapacitor will impact the renewable power production in this case study, but that the extent to which it will is not alarming.

6.4. Comparing voltage fluctuation mitigation options

This section compares the results for the different voltage fluctuation mitigation alternatives (Section 6.3.) for each of the scenarios (Section 6.2.). This was done in order to be able to assess which of the voltage fluctuation mitigation options is most suitable for the analyzed Lombok LV grid. Firstly, the sorted absolute voltage flicker plots are discussed for each scenario separately. These plots are supported by the quantified results presented in Table 10. Afterwards a part of the voltage fluctuation profile from the 100% PV base scenario was compared to the voltage fluctuation profiles from each of the different solutions for the same scenario. This was done in order to visualize the effect of each of the different solutions and to be able to analyze them more in depth.

Figure 26 presents the voltage flicker plot for each of the solutions in the 40% PV scenario, as well as the base results in this scenario. Table 10 quantifies the voltage flicker and voltage flicker reduction corresponding to Figure 26. Figure 26 shows that the 6-second capacitor option performs best in this scenario, since it has the smallest voltage fluctuations at almost all time steps. However, Table 10 shows that the 6-second capacitor does not experience the least amount of visible flicker, this is the curtailment option. This can also be seen in Figure 26, where it can be seen that the curtailment line is below the supercapacitor line roughly between the 3 and 10 most fluctuating time steps. The big disadvantage for the curtailment option it is the only solution which experiences annoying flicker. This is a result from the few time steps where attempts to counter voltage fluctuations actually result in larger voltage fluctuations. As previously discussed, this could problem could potentially be countered by determining a unique curtailment strategy for each individual PV system. However, this would require a lot of computing power, which might not be realistic. The grid reinforcement line is above the supercapacitor line at all of the time steps. It can therefore be concluded that grid reinforcement is not the best option in the 40% PV scenario.

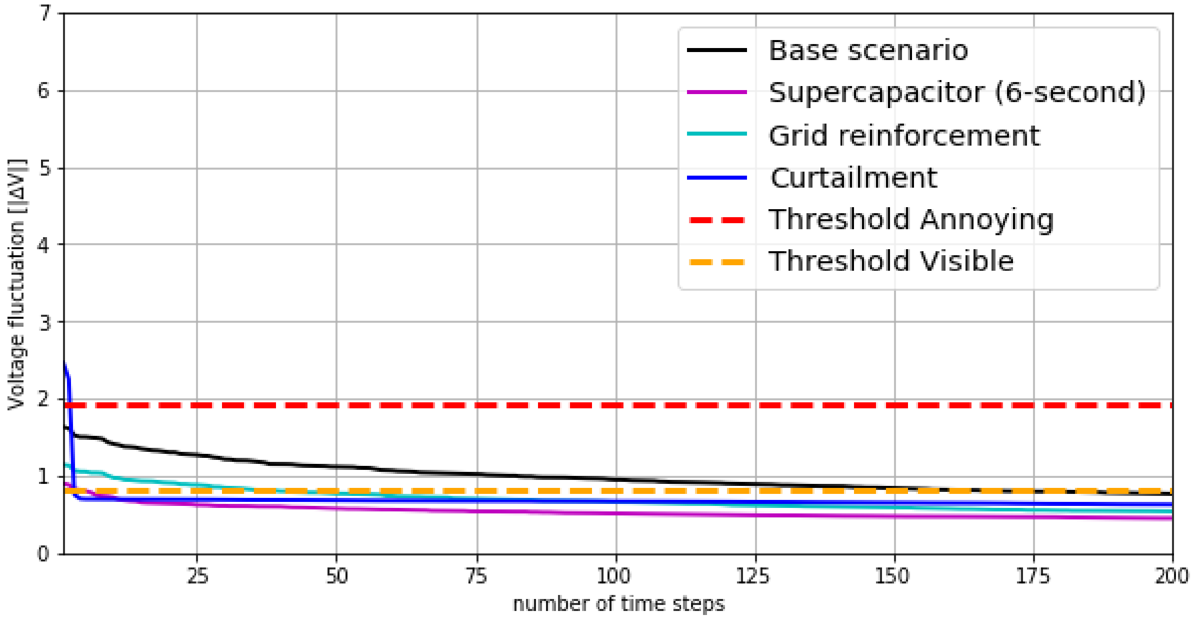

Figure 26: Voltage fluctuations in the 40% PV scenario for the different options combined – sorted by magnitude

Figure 27 presents the voltage flicker plot for each of the solutions in the 70% PV scenario, as well as the base results in this scenario. Table 10 quantifies the voltage flicker and voltage flicker reduction corresponding to Figure 27. The results of the 70% PV scenario show that the curtailment solution is no longer the solution with most visible voltage flicker reduced, this is the 10-second supercapacitor. Figure 27 furthermore shows that the difference between the reinforcement and the supercapacitor option has increased. This can be explained by the fact that in this scenario, the 10-second supercapacitor was used, whereas in the 40% PV scenario, the 6-second capacitor was used. This is because the supercapacitor produces a more smooth, and thus less fluctuating profile, the longer the time it should be able to store energy. Furthermore, the supercapacitor is the only solution which results in no annoying voltage flicker being left in this scenario. Similarly to the 40% scenario, the curtailment option experiences the largest voltage fluctuations. However, for most of the time steps is experiences smaller fluctuations compared to grid reinforcement. Following from the fact that the supercapacitor line is at all times below the grid reinforcement and curtailment lines, it can be concluded that the supercapacitor can be seen as the most desirable option to reduce voltage flicker from a technical perspective in the 70% PV scenario.

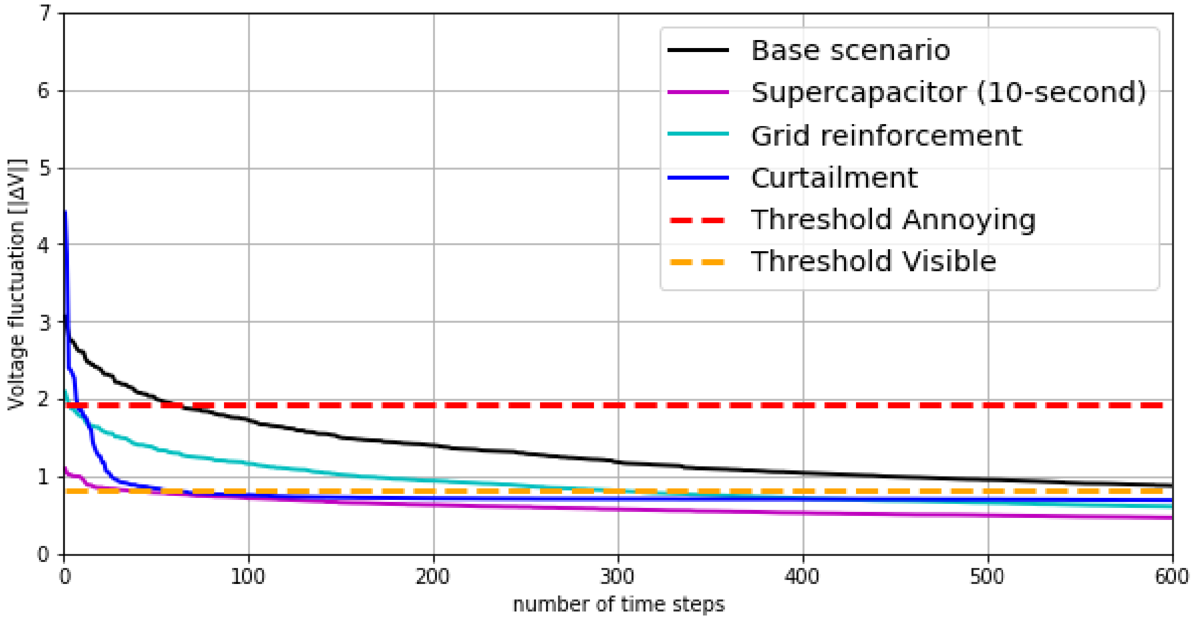

Figure 27: Voltage fluctuations in the 70% PV scenario for the different options combined – sorted by magnitude

Figure 28 presents the voltage flicker plot for each of the solutions in the 100% PV scenario, as well as the base results in this scenario. Table 10 quantifies the voltage flicker and voltage flicker reduction corresponding to Figure 28. Similarly to the 70% PV scenario, the (20-second) supercapacitor is also the only solution which does not experience any annoying flicker. Moreover, the solution performs best on all time steps. The 100% PV scenario is the first scenario in which the grid reinforcement option experiences the most annoying flicker. It can be safely stated that the reinforcement option is the least resilient of the solutions to an increase in installed solar PV capacity. The results for curtailment show that regardless of the scenario, it is able to mitigate a large share of the voltage flicker, which makes it an interesting option for voltage flicker mitigation. However, a solution for the largest voltage fluctuations has to be found for it to be competitive to the supercapacitor option.

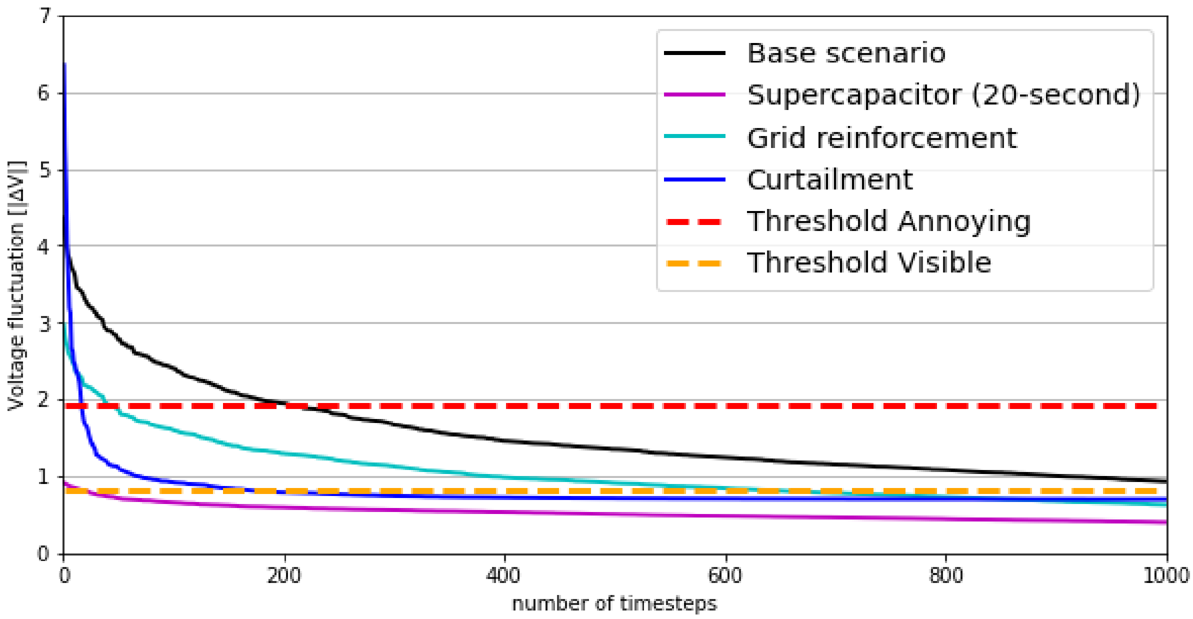

Figure 28: Voltage fluctuations in the 100% PV scenario for the different options combined – sorted by magnitude

Table 10: Flicker occurrence for scenarios and proposed solutions

	Flicker		***Flicker reduced***	
	Visible [%]	Annoying [%]	*Visible [%]*	*Annoying [%]*
		40%		
Base scenario	0.96	0	-	-
Curtailment	0.01	0.01	*98.71*	*Increase*
Reinforcement	0.21	0	*78.21*	-
Capacitor (6-second)	0.02	0	*98.08*	-
		70%		
Base scenario	4.26	0.37	-	-
Curtailment	0.33	0.04	*92.29*	*88.32*
Reinforcement	1.78	0.02	*58.12*	*95.00*
Capacitor (10-second)	0.19	0	*95.51*	*100.0*
		100%		
Base scenario	7.37	1.27	-	-
Curtailment	1.01	0.10	*86.31*	*91.80*
Reinforcement	3.86	0.26	*47.57*	*79.61*
Capacitor (20-second)	0.09	0	*98.83*	*100.0*

Figure 29 shows the voltage fluctuation profiles for one hour during 4 August 2017 for each of the different solutions in the 100% PV scenario. The 100% PV scenario was chosen to present because it shows the effect of the different options most clearly. Figure 29a shows the initial voltage fluctuation profile. It can be seen that it crosses the thresholds for annoying and visible flicker quite often. This gives an idea on how often people would experience voltage flicker with a sharp increase in installed solar PV capacity if there would not be any interference.

When we compare the Figure 29a to Figure 29c, we can see that there is close resemblance between the two figures. However, the extent to which the voltage fluctuates is less in Figure 29c. This shows that the grid reinforcement option is not a solution to the voltage flicker problem, it merely is a way to reduce the magnitude of the problem.

Comparing Figure 29a to Figure 29b shows that curtailment has impact on only the fluctuations which are larger than the visible voltage threshold. This is because power was only curtailed when $|\Delta V|$ exceeds $0.70V$. The rest of the voltage fluctuations remain equal to the initial profile. The advantage of this method is that no renewable electricity is lost when it does not have to be lost and that no system changes are required if a smart inverter is present. The disadvantage of this method clearly shows in the larger fluctuations that occur due to the different PV profiles for each household. Possible solutions to this problem are discussed in Section 7.3.

Comparing Figure 29a and 29d shows that the supercapacitor has effect on all voltage fluctuations, not only the ones above a certain threshold. Figure 29d clearly shows that it reduces the voltage fluctuations most effectively. Therefore, it is safe to conclude that Figure 29 confirms the previously drawn conclusion that the supercapacitor is the most effective option for voltage fluctuation mitigation in the Lombok area.

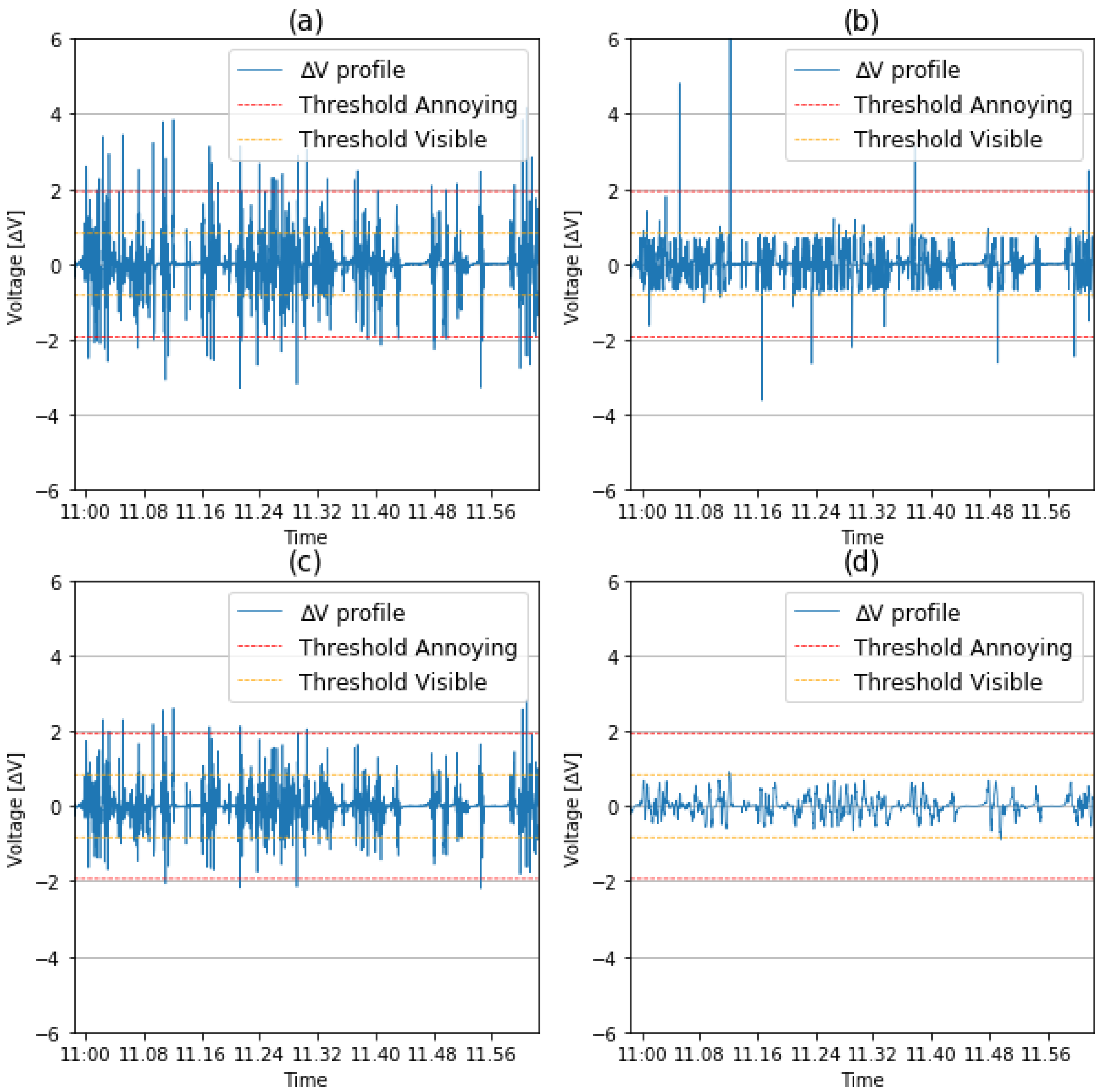

Figure 29: a) Voltage fluctuations 100% PV scenario 11:00-12.00 – no interference b) Voltage fluctuations 100% PV scenario 11:00-12.00 – curtailment c) Voltage fluctuations 100% PV scenario 11:00-12.00 – grid reinforcement d) Voltage fluctuations 100% PV scenario 11:00-12.00 – supercapacitor

There are slight differences when comparing the voltage fluctuation profiles of the solutions in the 100% PV scenario with the profiles in the 40% PV scenarios. Appendix C aims to show and explain these differences.

7. Discussion

This section aims to put the results in a wider perspective. This was done by discussing the model used, assumptions made, the magnitude of the voltage flicker problem, if and how this case study can be generalized and to what extent the different solutions are capable to contribute to voltage fluctuation mitigation. Furthermore, the results are compared to those in other studies and the practical implications of the solutions are discussed. Moreover, conclusions are drawn with regard to the most suitable voltage fluctuation mitigation option and to what policy implications this would lead. Lastly, recommendations for further research are discussed.

7.1. Methods and data input

In order to be able to determine the magnitude of the voltage flicker problem, as well as the potential impact of the different solutions, the grid modeling software PowerFactory was used. PowerFactory is widely used for modeling the electricity grid, and it can therefore be safely stated that it generates a realistic output if the designed grid and the input of the model are accurate. The designed grid can be evaluated as accurate since all the values in the modelled Lombok LV grid were based on the actual grid layout of the area. The length, location and technical specifications of each individual cable were determined by using Stedin documentation of the Lombok grid. However, the input into the model has been based on assumptions and simplifications and is therefore not as accurate as the grid layout.

The first simplification made is that the household demand profiles used are not from the Lombok area, and also not from 4 August 2017. The household demand profiles were obtained from Stedin employees of whom their houses we equipped with a device which read their electricity consumption through their smart meters on a one-minute interval for a week. These measurements were done in June 2019, October 2019, December 2019 and February 2020, which are not representative for household demand in August. Furthermore, extrapolating the demand profiles used, results in an average yearly electricity use of 2797 kWh, which is more or less equal to the Dutch average of 2790 kWh in 2018 (CBS, 2020), but more than the 2090 kWh yearly average electricity use in the Lombok area (CBS, 2017).

Additionally, the profiles had to be transformed into two-second demand profiles to match the PV data which also required assumptions and simplifications. Another simplification in the model is that special buildings such the school, shops and kindergartens received a household demand profile because of the absence of specific demand profiles which can be seen as representative for these buildings. However, adding realistic demand profiles for these special buildings would most likely not affect the results of this thesis since the results indicate that all severe voltage fluctuations are caused by solar PV and not the electricity demand.

Furthermore, it was assumed that there is perfect balance among the three phases of the LV grid cables and it was assumed that the attached MV grid to the Lombok area does not have effect on the LV grid, which in reality it does. These choices were made because it is impossible to predict which (newly installed) solar PV systems will be operating on which of the three phases, even if 3-phase inverters are widely installed. Furthermore, it is unclear what exactly the effect of the MV grid on the LV grid would be if the installed solar PV capacity increases.

Even though the aforementioned assumptions and simplifications might be very significant, they do not greatly affect the value of the thesis. This thesis aims to explore the effect of an increasing solar PV capacity on voltage fluctuations and to assess whether different solutions could be suitable to mitigate these fluctuations. In order to do this, accurate solar PV power production data and accurate modeling of the different solutions are the most important. Very accurate demand profiles and balances in cables are not required to show trends and meet the explorative aim of this thesis.

7.2. Identifying the problem

The magnitude of the voltage flicker problem was assessed for the current situation as well as for the 40%, 70% and 100% PV scenarios. The results for the current situation show that no visible voltage flicker has been present so far in the Lombok LV grid. This is an expected result, since Stedin did not yet receive voltage flicker complaints for this specific location. The reason that there has not yet been a problem in the Lombok LV grid can be attributed to relatively short LV cables which results in a relatively low resistance in the grid. Furthermore, currently only 6% of the households that can install solar PV in the Lombok area (4% of all households) have done so. This much lower than the Dutch average of 13%. Therefore, no voltage flicker in the current situation is a logical result. In the different solar PV penetration scenarios, visible (all scenarios) and annoying (70% and 100% scenarios) voltage flicker values were found. The results show that the larger the installed solar PV capacity, the larger the voltage fluctuations in the LV grid. Besides the installed PV capacity, no other changes were made in the model in the different scenarios. Therefore the voltage flicker can be entirely attributed to solar PV. The fact that an increasing problem was found with an increasing solar PV capacity shows that without interference, most likely there will be a significant problem in the future.

The extent of the problem will most likely be even larger than the simulations suggest for six reasons. Firstly, the individual solar PV profiles were generated by using the inverse distance weighted interpolation method. Because this method uses averages of the known data points, the resulting solar PV profiles experience less sharp peaks. The least fluctuating generated PV profile experiences 13% less voltage fluctuations compared to the initial solar PV profiles. In reality, the voltage fluctuations in the LV grid will thus be larger than measured in this thesis.

Secondly, the demand profiles were generated using linear interpolation, this created relatively smooth demand profiles. In reality, the demand profiles of households experience sharp peaks because of the switching on or off of high power electrical appliances such as a water cooker. Realistic demand profiles can therefore also have an effect on voltage flicker.

Thirdly, because of a rapid increase in installed heat pumps and driven EVs in the Netherlands, it is expected that the electricity demand will grow rapidly in the near future (van Zoest et al., 2014). The larger the electricity demand, the larger the chance that this will have an effect on the voltage flicker.

Furthermore, the aforementioned simplification regarding the perfect balance over the three phases within the LV grid cables results in the least possible voltage fluctuations. Whenever one of the phases experiences more electricity flowing through, which will happen because it is impossible to always have perfect balance in the cables, this phase experiences heavier voltage fluctuations, thus increasing the voltage flicker problem.

Another reason for the voltage fluctuations being larger than simulated is that the effect of voltage fluctuations in the MV grid on the LV grid has been disregarded because of the assumed equal loading in the MV cables throughout the entire day. In reality voltage fluctuations in the MV grid occur, and they affect in the LV grid.

Lastly, the analyzed Lombok area has relatively short cables because it is a densely populated area, it therefore has lower resistance in its cables which result in smaller voltage fluctuations. Also, there is relatively little available roof for solar PV systems in the Lombok area compared to the rest of the Netherlands. When the same study would be executed for other parts of the Netherlands, it is likely that these will experience more voltage fluctuations.

Because of the fact that the extent of the problem will most likely be larger in reality and in other parts of the LV grid in the Netherlands, finding problems in this case study most likely means that these problems will occur throughout most parts of the Dutch LV grid when the installed solar PV capacity rises without interference. Even though the problem is severe in days similar to 4 August 2017, this does not mean that the problem will be prominent throughout the year. The analyzed day 4 August 2017 was the day in 2017 with most fluctuations in PV power output, but it is not an extreme outlier compared to other days with much fluctuation. This suggests that the problem will be prominent in a significant amount of days throughout the year if the installed solar PV capacity rises.

Hence, it is safe to conclude that interference is required to be able to maintain a high power quality. This thesis identified four different types of solutions to interfere and therewith actively mitigate voltage fluctuations resulting from an increasing solar PV capacity. These solutions are active power curtailment, reactive power control, EES and grid reinforcement. The reactive power control solution was disregarded because of the presumed small potential effect in the Lombok LV grid because of its low R/X ratios. However, this does not mean that this option has no potential to be effective in other parts of the Dutch LV grid, and it likely is an effective solution in the MV grid (Shivashankar et al., 2016).

7.3. Voltage fluctuation mitigation options

The first analyzed voltage fluctuation mitigation option in this thesis was active power curtailment. Here power production from solar PV systems were strategically curtailed based on the voltage in the LV cables in the system. As discussed in the results (Section 6.3.1.), the curtailment strategy used produces some larger peaks in voltage fluctuation because the LV grid was curtailed based on the voltage at one point in the grid. A few conclusions can be drawn from these results.

Firstly, one measurement point in the Lombok LV grid was not enough to be able to use this curtailment strategy to curtail the PV power without generating larger peaks at that point. The analyzed Lombok area is approximately 0.05 km^2. For this curtailment strategy to be effective, multiple measurement points would be required in the small analyzed grid. If one would want to apply this curtailment strategy throughout the Netherlands, a possibly unrealistic amount of measurement devices would have to be placed throughout the grid, and an enormous amount of data would have to be processed in order to do so. However, if this could be done, the mitigation potential of the curtailment strategy is very significant and it should even be able to mitigate all voltage flicker.

Secondly, the curtailment strategy used, assumed perfect foresight to determine when to curtail preventively. In reality, perfect foresight is not possible to have. Cloud Prediction Technology (CPT) is a possible tool that could be used to approach this perfect foresight (Dickeson et al., 2019). However, this would again require extra measurements, investments and data processing. In short, the used curtailment strategy could potentially work, it does not require a lot of renewable power curtailment, but it would require a lot of measurements and data processing. Static curtailment strategies could potentially overcome the problem of the amount of data required for curtailment. However, these methods are often less effective in voltage control and require a larger amount of power to be curtailed (Hashemi & Østergaard, 2016).

The second analyzed voltage fluctuation mitigation option in this thesis was grid reinforcement. Here the cables in the modelled LV grid were changed to stronger cables with a lower resistance to reduce voltage fluctuations. The results (Section 6.3.2.) show that grid reinforcement works to reduce voltage fluctuations, but it is not enough to mitigate all voltage flicker. Especially when the installed solar PV capacity increases, the mitigating effect of grid reinforcement declines.

This thesis showed the maximum potential effect of grid reinforcement by replacing all cables. As pointed out in Section 6.3.2., this is not realistic. However, the reason to show the maximum potential effect is that if this option is not sufficient, it would not have to be considered as a solution in the future. The results show that this is the case. Hence, replacing LV cables does not have to be considered as a possible solution to mitigate voltage flicker.

As described in Section 2., grid reinforcement through redirecting cables has been mentioned by Stetz, Marten & Braun (2012) as an alternative to replacing cables. With this method, load could be redirected from weak points in the LV grid so that fewer voltage fluctuations would occur here. As discussed in Section 4.3.2., modelling this option has been considered in this thesis. However, since the scenario results showed voltage flicker everywhere within the analyzed LV grid, there was no weak point to redirect load away from. Consequently, this option was disregarded.

The last potential solution analyzed in this thesis was the use of a supercapacitor to smoothen the power output from the PV systems. The choice was made to model the supercapacitor in such a way that it produces a moving average of a pre-defined time step of the power coming into the supercapacitor. The reason to choose this method is that it is relatively easy to incorporate and because it has been used in literature, for example by Carvalho, Bataglioli and Coury (2018) and Chong et al. (2017). The results (Section 6.3.3.) show that this option is most suitable for voltage flicker mitigation from a technical perspective. Further advantages of the supercapacitor include that it is easily scalable. There are many different types of supercapacitors on the market, so for every solar PV system, an appropriate supercapacitor should be able to be found quite easily. Furthermore, once the supercapacitor has been placed and set up, no extra work would be required.

The major disadvantages of using a supercapacitor is that there would be extra costs for PV systems, both because of equipment costs and efficiency losses. The price of supercapacitors is about 10,000 €/kWh (Yan, 2015), which is 10 €/Wh. This would translate to €49.70 for an average 3.6 kWp solar PV system if power would have to be stored for 20 seconds. A DC/DC converter would also be required in a PV system set-up with a supercapacitor. The DC/DC converters are roughly the same price as the supercapacitors. We can therefore estimate the total extra costs of the PV system with supercapacitor to be about €100 for an average system. Taking the efficiency of the supercapacitor and DC/DC converter (about 98%) into account, assuming a combined round-tip efficiency of 95%, an initial system price of €7,000 and an initial payback period of 7 years, adding the supercapacitor would increase the payback period by 5.7 months, this is significant but not insurmountable. Another disadvantage is that there is currently no incentive for (potential) solar PV system owners to add the supercapacitor to their system. Therefore, extra legislation is required to oblige consumers to add a supercapacitor module.

When we compare the three different options, based on results of the grid reinforcement option, plus the fact that this option would not be realistic to apply everywhere, grid reinforcement can be disregarded as a serious option for voltage flicker mitigation. Based on the results in this thesis, the supercapacitor is the most desirable option for voltage flicker mitigation. It should even be able to mitigate all voltage flicker as long as the supercapacitor is large enough. However, if CPT could be applied, many real time voltage measurements could be done and if the required computing power would not be an obstacle, active power curtailment could be able to mitigate all voltage flicker as well. If this could be done, active power curtailment is most likely cheaper than the supercapacitor option (disregarding the costs to apply CPT) because the curtailment option curtailed at most 2.26% of all power produced. This only happens when there are many severe voltage fluctuations, at an average day less power would have to be curtailed. The costs of "lost" electricity would therefore be lower than the "lost" electricity caused by the efficiency losses from the DC/DC converter and supercapacitor in the supercapacitor solution. However, since the large scale applicability of the curtailment option is far from certain, because the supercapacitor requires less work and produces better results in this thesis, this thesis concludes that the supercapacitor option is best suitable for voltage flicker mitigation in the LV grid.

The suitability of using a supercapacitor for voltage flicker mitigation has been confirmed in scientific literature. Sahay and Dwivedi (2009) performed a literature review in different supercapacitor applications for power quality improvement. Based on a study by Kazimierczuk and Cravens (1996), they stated that the supercapacitor was able to regulate voltage effectively in various operating conditions for up to 35 seconds. The 20-second moving average used in the 100% PV scenario in this thesis should therefore be achievable. Based on research by Li et al. (2008), Sahay and Dwivedi conclude that a supercapacitor is suitable for smoothening wind power caused voltage fluctuations, which suggests that the supercapacitor would also be applicable for solar PV voltage flicker mitigation. Based on all the literature reviewed, Sahay and Dwivedi (2009) conclude that a supercapacitor is a good option for power quality maintenance, if the prices of the supercapacitors drop. The prices for supercapacitors have decreased considerably since the Sahay and Dwidevi made their conclusions. Since 2008, the market of supercapacitors increased by on average 39% per year, which resulted in a rapid decline in price (Huang et al., 2019). Yin et al. (2017) performed real measurements for a hypothetical stand-alone micro grid with solar PV as a power source. In this micro grid, they used a supercapacitor in order to reduce voltage fluctuations resulting from solar PV production. They conclude that the supercapacitor is suitable for this function. Even though a very different grid has been analyzed in the study by Yin et al., the ought application of the supercapacitor is similar. Therefore, it can be concluded that there is much potential for the actual application of the supercapacitor in the LV grid for voltage flicker mitigation.

7.4. Implications and recommendations

Even though the literature and the results of this thesis indicate that the supercapacitor is a very promising option to reduce voltage flicker in the LV grid, one major hurdle would have to be overcome for large scale application of the supercapacitor in the Dutch LV grid. This hurdle is the fact that currently there is no (financial) incentive for solar PV system owners to install a supercapacitor to their system since they cost money and slightly reduce the overall efficiency of the system, which both increase the pay-back time of the entire PV system. Therefore, in order for the supercapacitor to work, new regulation should be developed which obliges the installment of a supercapacitor for every new system installed. This thesis recommends to eventually do this through altering the IEC 60364-7-712 standard. This standard, amongst other things, specifies the installation criteria for solar PV power supply systems.

However, in order to update this IEC standard, first further research has to be conducted. The most important recommendation is to test the supercapacitor option in a test environment and to see how it performs compared to a similar setup without a supercapacitor. When these tests show promising results, it is recommended to test the supercapacitor in an actual part of the LV grid. Furthermore it is recommended to explore whether the supercapacitor also is the most suitable option for more remote, rural areas to see whether the type of LV grid analyzes has significant effect on the results. Another recommendation is to test whether the supercapacitor could be applied strategically throughout the AC part of the LV grid. In this case the supercapacitor might also be able to react to voltage fluctuations resulting from large electricity demand such as the increasing amount of heat pumps installed and an increasing EV fleet. Lastly, it is important to not disregard the active power curtailment option. It would be interesting to perform a more in depth analysis on multiple curtailment strategies in order to see whether these could potentially be of larger impact than the results of this thesis indicate.

8. Conclusion

This thesis aimed to show the impact of an increasing installed solar PV capacity in the LV grid on voltage flicker and the potential of 1) active power curtailment, 2) grid reinforcement and 3) using supercapacitors to mitigate this voltage flicker. In order to do so, a case study was performed on a part of the LV grid located in the neighborhood Lombok in Utrecht, the Netherlands.

The 40%, 70% and 100% PV penetration scenarios all show voltage flicker problems resulting from solar PV. The scenarios furthermore showed that the extent of the problem flicker will increase when the installed solar PV capacity increases. The extent of the problem is most likely even larger than modeled in this thesis because of the interpolation methods used, simplifications made to the grid modeled and limited resolution of available data.

Incorporating the different voltage regulation techniques showed that the grid reinforcement option is the option with the least potential for voltage flicker mitigation. Moreover, this option is the least realistic to implement and can therefore be disregarded as a suitable solution.

The active power curtailment option showed significantly more voltage flicker mitigation potential compared to the grid reinforcement option. Moreover, the active power curtailment has a limited amount of “lost” electricity with a maximum of 2.26% of the solar PV power output being curtailed. However, these results can only be achieved when the active power is curtailed at precisely the right time, which might be too difficult to achieve. One measuring point in the 0.05 km^2 Lombok area was insufficient to be able to curtail precise enough. At certain locations, the PV power output was curtailed a few seconds too late or early, resulting in even larger voltage fluctuations compared to the scenario without interference. CPT might be a solution to this problem, but this would require more research.

The supercapacitor option showed the most reliable results and the largest potential for voltage flicker mitigation in all scenarios. Furthermore, the required supercapacitor size of 1.38 Wh/kWp can be met relatively easy with supercapacitors that are currently in the market. However, the supercapacitors would reduce the overall efficiency and increase the price of the solar PV systems which they are attached to. As a result, this thesis estimates the pay-back time of a solar PV system with a supercapacitor to be 6% longer compared to a system without a supercapacitor. Since there is no direct incentive for consumers to add the supercapacitor to their solar PV system, legislation would have to be installed to make a supercapacitor a mandatory component in a solar PV system.

In conclusion, this research sees most potential for the supercapacitor option and recommends to explore the effect of supercapacitors in more remote areas, to explore the potential of strategic placement of supercapacitors in the AC part of the LV grid and to build a set-up to test the supercapacitor. If these results are positive as well, it is recommended to change legislation so that a supercapacitor becomes a required component in a solar PV system.

References

Argyrou, M. C., Paterakis, F., Panagi, C., Makarounas, C., Darwish, M., & Marouchos, C. C. (2018). Supercapacitor application for PV power smoothing. In 2018 53rd International Universities Power Engineering Conference (UPEC) (pp. 1-5). IEEE.

Ari, G. K., & Baghzouz, Y. (2011). Impact of high PV penetration on voltage regulation in electrical distribution systems. In *2011 International Conference on Clean Electrical Power (ICCEP)* (pp. 744-748). IEEE.

Bofinger, S., & Heilscher, G. (2006). Solar electricity forecast-approaches and first results. In 21st European Photovoltaic Solar Energy Conference, Dresden. (pp. 4–8).

Brinkel, N. B. G., Gerritsma, M. K., AlSkaif, T. A., Lampropoulos, I., van Voorden, A. M., Fidder, H. A., & van Sark, W. G. J. H. M. (2020). Impact of rapid PV fluctuations on power quality in the low-voltage grid and mitigation strategies using electric vehicles. *International Journal of Electrical Power & Energy Systems*, *118*, 105741.

Carvalho, W. C., Bataglioli, R. P., & Coury, D. V. (2018). Comparison of supercapacitor storage system control methods for wind power smoothing. In *2018 Simposio Brasileiro de Sistemas Eletricos (SBSE)* (pp. 1-6). IEEE.

Centraal Bureau voor de Statistiek. (2017). Kerncijfers wijken en buurten. Retrieved from: https://www.cbs.nl/nl-nl/maatwerk/2017/31/kerncijfers-wijken-en-buurten-2017

Centraal Bureau voor de Statistiek. (2018). Vermogen zonnepanelen meer dan de helft toegenomen. Retrieved from: https://www.cbs.nl/nl-nl/nieuws/2019/17/vermogen-zonnepanelen-meer-dan-de-helft-toegenomen

Centraal Bureau voor de Statistiek. (2020). Energieverbruik particuliere woningen; woningtype en regio's. Retrieved from:
https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81528NED/table?fromstatweb

Chaudhary, P., & Rizwan, M. (2018). Voltage regulation mitigation techniques in distribution system with high PV penetration: A review. *Renewable and Sustainable Energy Reviews*, *82*, 3279-3287.

Chong, L. W., Wong, Y. W., Rajkumar, R. K., & Isa, D. (2017). Modelling and simulation of standalone PV systems with battery-supercapacitor hybrid energy storage system for a rural household. *Energy Procedia*, *107*(1), 232-236.

Das, C. K., Bass, O., Kothapalli, G., Mahmoud, T. S., & Habibi, D. (2018). Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality. Renewable and Sustainable Energy Reviews, 91, 1205-1230.

De la Parra, I., Marcos, J., García, M., & Marroyo, L. (2015). Control strategies to use the minimum energy storage requirement for PV power ramp-rate control. *Solar Energy*, *111*, 332-343.

Dickeson, G., McLeod, L., Dobb, A., Frearson, L., Herteleer, B., & Scheltus, D. (2019). RAMP RATE CONTROL FOR PV PLANT INTEGRATION: EXPERIENCE FROM KARRATHA AIRPORT'S HYBRID POWER STATION. 36th European Photovoltaic Solar Energy Conference and Exhibition, Marseille. (pp. 1351-1356)

DIgSILENT GmbH. (2019). DIgSILENT PowerFactory 2019 SP2 [Computer software]. Gomaringen, Germany. Available at https://www.digsilent.de/en/powerfactory.html.

Di Piazza, A., Di Piazza, M. C., & Vitale, G. (2009). A kriging-based partial shading analysis in a large photovoltaic field for energy forecast. In *Int. Conference on Renewable Energies and Power Quality (ICREPQ), Spain, April 15-17, 2009*.

Droste-Franke, B., Paal, B., Rehtanz, C., Sauer, D. U., Schneider, J. P., Schreurs, M., & Ziesemer, T. (2012). *Balancing renewable electricity: energy storage, demand side management, and network extension from an interdisciplinary perspective* (Vol. 40). Springer Science & Business Media.

Espinar, B., & Mayer, D. (2011). The role of energy storage for mini-grid stabilization. Retrieved from: https://hal-mines-paristech.archives-ouvertes.fr/hal-00802927

European Commission. (2017). Study on "Residential Prosumers in the European Energy Union". *GfK Belgium consortium.* Retrieved from: https://ec.europa.eu/commission/sites/beta-political/files/study-residential-prosumers-energy-union_en.pdf

Fraunhofer Institute for Solar Energy Systems, ISE. (2019). Photovoltaics Report. Retrieved from: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

Van Gastel, E. & De Jonge Baas, M. (2019). WoonOnderzoek Nederland: 13 procent eengezinswoningen heeft zonnepanelen. *Solar Magazine.* Retrieved from: https://solarmagazine.nl/nieuws-zonne-energie/i18269/woononderzoek-nederland-13-procent-eengezinswoningen-heeft-zonnepanelen

Gekakis, N., Nadeau, A., Hassanalieragh, M., Chen, Y., Liu, Z., Honan, G. & Soyata, T. (2015). Modeling of supercapacitors as an energy buffer for cyber-physical systems. Cyber-Physical Systems—A Computational Perspective, 171-189.

Google Earth Pro Version 7.3. (2019). Imagery Date: 8/24/2019. Floresstraat, Utrecht. 52 05'25.42"N, 5 06'02.47"E.

Gueymard, C. A. (2017). Cloud and albedo enhancement impacts on solar irradiance using high-frequency measurements from thermopile and photodiode radiometers. Part 1: Impacts on global horizontal irradiance. *Solar Energy*, *153*, 755-765.

Van Haaren, R., Morjaria, M., & Fthenakis, V. (2014). Empirical assessment of short-term variability from utility-scale solar PV plants. *Progress in Photovoltaics: Research and Applications*, *22*(5), 548-559.

Hashemi, S., & Østergaard, J. (2016). Methods and strategies for overvoltage prevention in low voltage distribution systems with PV. IET Renewable power generation, 11(2), 205-214.

Huang, S., Zhu, X., Sarkar, S., & Zhao, Y. (2019). Challenges and opportunities for supercapacitors. *APL Materials*, *7*(10), 100901.

International Electrochemical Commission. (2011). Electrical Energy Storage – *White paper.* Retrieved from: https://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf

International Electrochemical Commission. (2017). Standard 61000-4-15:2010/ISH1:2017 - *Electromagnetic compatibility (EMC) - Part 4-15: Testing and measurement techniques - Flickermeter - Functional and design specifications.*

International Energy Agency. (2019a). Global Energy and CO_2 Status Report. Retrieved from: https://www.iea.org/geco/electricity/

International Energy Agency. (2019b). Renewables 2019 – Analysis and forecast to 2024. Retrieved from: https://webstore.iea.org/download/summary/2853?fileName=1.%20English-Renewables-2019-ES.pdf

Jamaly, M., & Kleissl, J. (2017). Spatiotemporal interpolation and forecast of irradiance data using Kriging. *Solar Energy*, *158*, 407-423.

Kazimierczuk, M. K., & Cravens, R. C. (1996). Application of super capacitors for voltage regulation in aircraft distributed power systems. In *PESC Record. 27th Annual IEEE Power Electronics Specialists Conference* (Vol. 1, pp. 835-841). IEEE.

Kim, J., Suharto, Y., & Daim, T. U. (2017). Evaluation of Electrical Energy Storage (EES) technologies for renewable energy: A case from the US Pacific Northwest. *Journal of Energy Storage*, *11*, 25-54.

Li, J., & Heap, A.D. (2011). A review of comparative studies of spatial interpolation methods in environmental sciences—performance and impact factors: *Ecological Informatics*, v. 6, p. 228–241.

Li, X., Hu, C., Liu, C., & Xu, D. (2008). Modeling and control of aggregated super-capacitor energy storage system for wind power generation. In *2008 34th Annual Conference of IEEE Industrial Electronics* (pp. 3370-3375). IEEE.

Maxwell Technologies. (2009). Product Guide – Maxwell Technologies BOOSTCAP Ultracapacitors – *Doc. No. 1014627.1*. Retrieved from:
https://www.maxwell.com/images/documents/PG_boostcap_product_guide.pdf

Mohammadi, P., & Mehraeen, S. (2016). Challenges of PV integration in low-voltage secondary networks. *IEEE Transactions on Power Delivery*, *32*(1), 525-535.

NEN. (2010). Standard NEN-EN 50160:2010 en - *Voltage characteristics of electricity supplied by public electricity networks Voltage characteristics of electricity supplied by public electricity networks.*

Oirsouw, van P. (2012). Netten voor distributie van elektriciteit. Phase to Phase B.V.

Olowu, T. O., Sundararajan, A., Moghaddami, M., & Sarwat, A. I. (2018). Future challenges and mitigation methods for high photovoltaic penetration: A survey. Energies, 11, 1782.

PlanBureau voor de Leefomgeving. (2019). Effecten ontwerp klimaatakkoord. Retrieved from: https://www.pbl.nl/sites/default/files/downloads/pbl-2019-effecten-ontwerp-klimaatakkoord_3619_1.pdf

Qual-Tech Engineers, Inc. (2015). The History of Flicker Limits. *The Electrical Power Engineers.* Retrieved from: https://www.qualtecheng.com/docs/arc-furnace-applications/QT-621.pdf.

Python Software Foundation. (2019). Python Language Reference, version 3.7 [Computer software]. Beaverton, USA. Available at http://www.python.org

Sahay, K., & Dwivedi, B. (2009). Supercapacitors energy storage system for power quality improvement: An overview. *J. Energy Sources*, *10*(10), 1-8.

Van Sark, W. G. J. H. M. (2019). Photovoltaic system design and performance. Energies, 12, 1826.

Stetz, T., Marten, F., & Braun, M. (2012). Improved low voltage grid-integration of photovoltaic systems in Germany. *IEEE Transactions on sustainable energy*, *4*(2), 534-542.

Shivashankar, S., Mekhilef, S., Mokhlis, H., & Karimi, M. (2016). Mitigating methods of power fluctuation of photovoltaic (PV) sources–A review. *Renewable and Sustainable Energy Reviews*, *59*, 1170-1184.

Spring, A., Wirth, G., Becker, G., Pardatscher, R., Witzmann, R., Brantl, J., & Schmidt, S. (2013). Effects of Flicker in a Distribution Grid with high PV Penetration. In *28th European Photovoltaic Solar Energy Conference and Exhibition* (p. 6).

Spring, A., Wirth, G., Becker, G., Pardatscher, R., & Witzmann, R. (2015). Grid influences from reactive power flow of photovoltaic inverters with a power factor specification of one. *IEEE Transactions on Smart Grid*, *7*(3), 1222-1229.

Von Appen, J., Braun, M., Stetz, T., Diwold, K., & Geibel, D. (2013). Time in the sun: the challenge of high PV penetration in the German electric grid. *IEEE Power and Energy magazine*, *11*(2), 55-64.

Wang, H., Liserre, M., Blaabjerg, F., de Place Rimmen, P., Jacobsen, J. B., Kvisgaard, T., & Landkildehus, J. (2013). Transitioning to physics-of-failure as a reliability driver in power electronics. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, *2*(1), 97-114.

Webster, R. & Oliver, M. A. (1993). How Large a Sample Is Needed to Estimate the Regional Variogram Adequately? Geostatistics Troia '92 , ed. A Soares, Vol 1, pp. 155-66. Kluwer Academic Publishers, Dordrecht.

Wilkins, A., Veitch, J., & Lehman, B. (2010). LED lighting flicker and potential health concerns: IEEE standard PAR1789 update. In *2010 IEEE Energy Conversion Congress and Exposition* (pp. 171-178). IEEE.

Wong, J., Lim, Y. S., Tang, J. H., & Morris, E. (2014). Grid-connected photovoltaic system in Malaysia: A review on voltage issues. *Renewable and Sustainable Energy Reviews*, *29*, 535-545.

Yan, R., Marais, B., & Saha, T. K. (2014). Impacts of residential photovoltaic power fluctuation on on-load tap changer operation and a solution using DSTATCOM. *Electric Power Systems Research*, *111*, 185-193.

Yan, J. (2015). *Handbook of Clean Energy Systems, 6 Volume Set* (Vol. 5). John Wiley & Sons.

Yang, C., Xu, Q., Xu, X., Zeng, P., & Yuan, X. (2014). Generation of solar radiation data in unmeasurable areas for photovoltaic power station planning. In *2014 IEEE PES General Meeting| Conference & Exposition* (pp. 1-5). IEEE.

Yang, X. X., & Kratz, M. (2009). Power system flicker analysis by RMS voltage values and numeric flicker meter emulation. IEEE Transactions on power delivery, 24(3), 1310-1318.

Yin, C., Wu, H., Locment, F., & Sechilariu, M. (2017). Energy management of DC microgrid based on photovoltaic combined with diesel generator and supercapacitor. *Energy conversion and management*, *132*, 14-27.

Van Zoest, P., Veldman, E., Lukszo, Z., & Herder, P. M. (2014). Analysis of future electricity demand and supply in the low voltage distribution grid. In *Proceedings of the 11th IEEE International Conference on Networking, Sensing and Control* (pp. 619-624). IEEE.

Appendices

Appendix A: Lombok divided in 10m x 10m grid

Figure 30 shows the image used to determine which solar PV profile corresponds to which household. The numbers in Figure 30 represent the used locations of the known solar PV systems and the yellow line encloses the analyzed LV grid. For each household it was manually assessed in what 10m x 10m box it fitted best. It can be seen that some 10m x 10m boxes were used multiple times and that some boxed were not used at all.

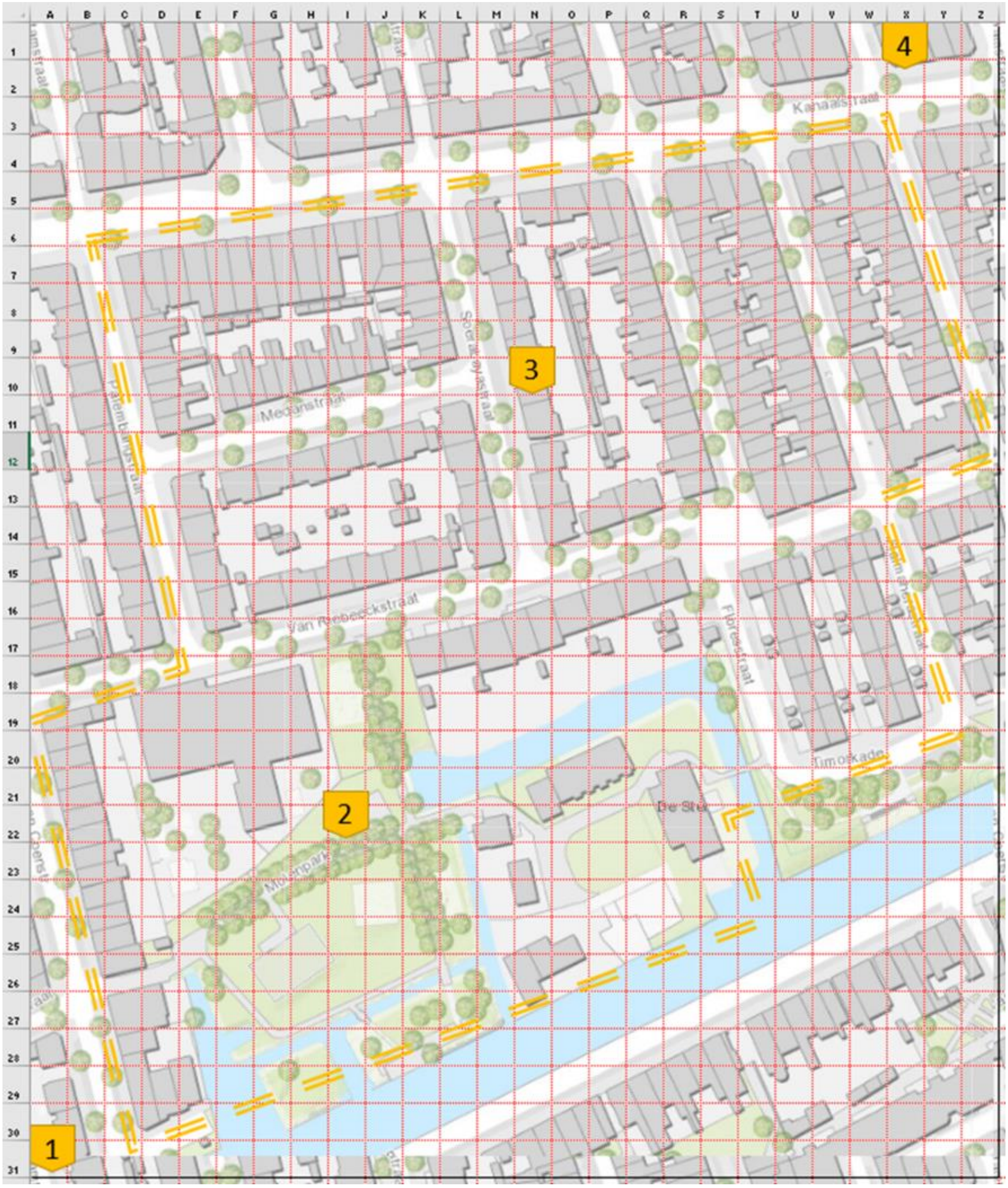

Figure 30: Lombok area divided in a 10m x 10m grid

Appendix B: Effect of grid reinforcement on other lines

The effect of grid reinforcement significantly differs per line. This is because different types of cables were all replaced by the same cable. For some cables this meant a slight reduction in resistance, for others there was a larger reduction in resistance. Figure 31 shows how the voltage fluctuation profiles differ per line. Figure 31a shows the situation without interference, Figure 31b shows the situation with interference. In both figures, Line 6 was highlighted since this line was used for the results in Section 6.3.2. Comparing Figure 31a shows that in the initial scenario there is a large difference in the extent of the voltage flicker problem among the different lines. After the grid reinforcement was applied (Figure 31b), the difference among the different lines was reduced significantly. From Figure 31 it can be deduced that for some lines, grid reinforcement has a significant effect, but for other lines it does not have much effect. This can be explained by the initial resistance in the cables, the smaller the reduction in resistance because of grid reinforcement, the smaller the voltage flicker mitigation. Furthermore, Figure 31 shows that Line 6 is one of the lines with most reduction in voltage fluctuations. Therefore, it can be concluded that the maximum effect of grid reinforcement will not be larger than described in Section 6.3.2.

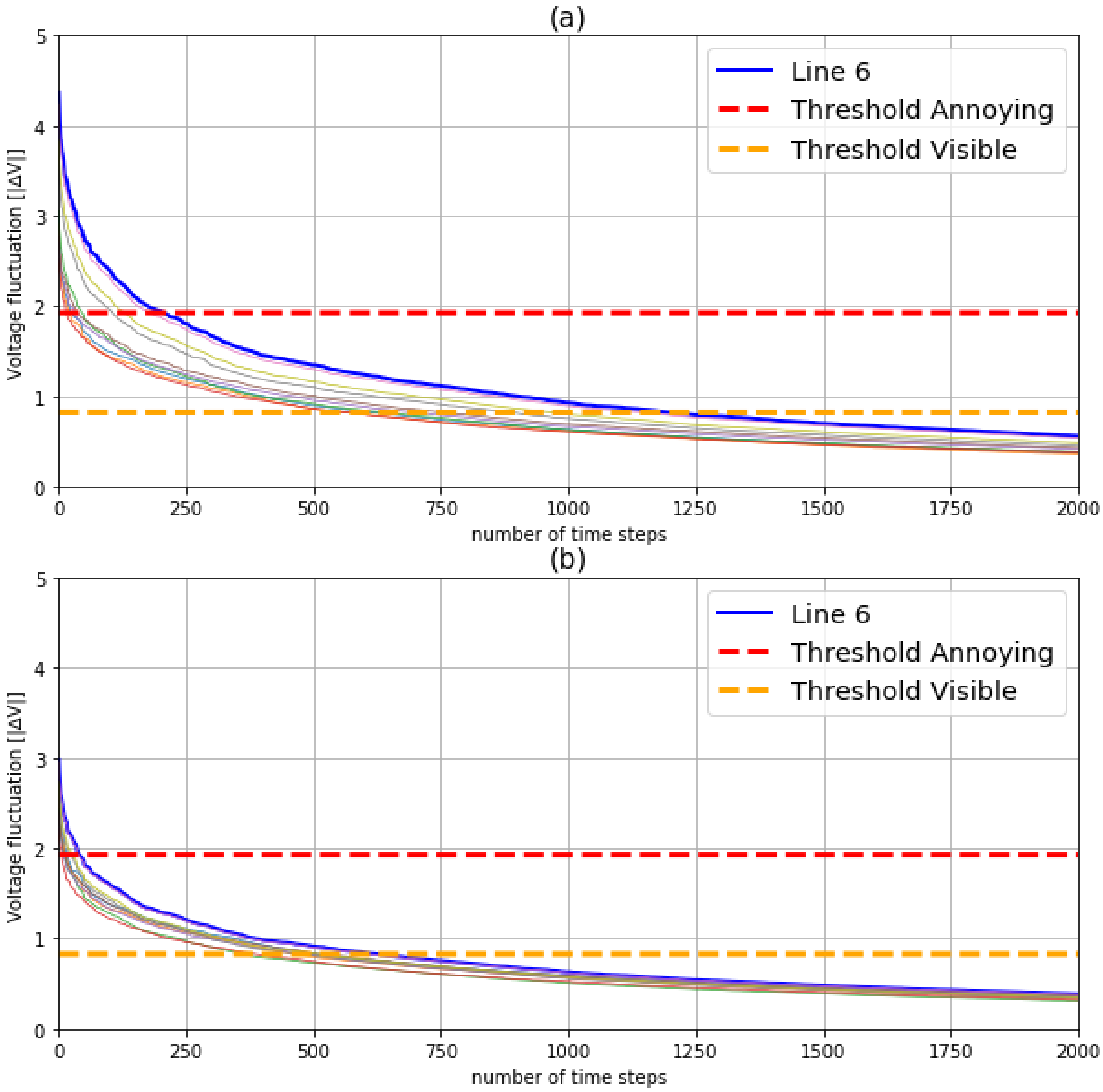

Figure 31: a) Voltage fluctuations 100% PV scenario for all analyzed lines without interference – sorted on magnitude b) Voltage fluctuations 100% PV scenario for all analyzed lines with grid reinforcement – sorted on magnitude

Appendix C: Voltage fluctuation profiles 40% and 70% scenario

Figure 32 and Figure 33 represent the voltage fluctuation profiles of the different voltage fluctuation mitigation techniques and the base scenario for the 40% and 70% scenarios respectively. The figures are similar to Figure 29, which is the same figure, but then for the 100% PV scenario.

Figure 32a shows the situation without interference in the 40% PV scenario. Similarly to the 100% PV scenario, the grid reinforcement option (Figure 32c) shows similar results, but to less fluctuating. In this scenario, the grid reinforcement option performs considerably better compared to the 100% PV scenario. This can be seen by the absence of very large voltage fluctuations. The curtailment option (Figure 32b) also shows similar results to the 100% PV scenario. The large difference between the two is that in this case, there is only one outlier, whereas in the 100% PV scenario there are multiple. This could be a result of the fewer PV systems in the area which can have a reinforcing effect on the voltage fluctuations. The supercapacitor option (Figure 32d) still shows the best results, but the profile is fluctuating more rapidly than in the 100% PV scenario. This is a result from the longer moving average used in the 100% PV scenario (20 seconds) compared to the 40% PV scenario (6 seconds).

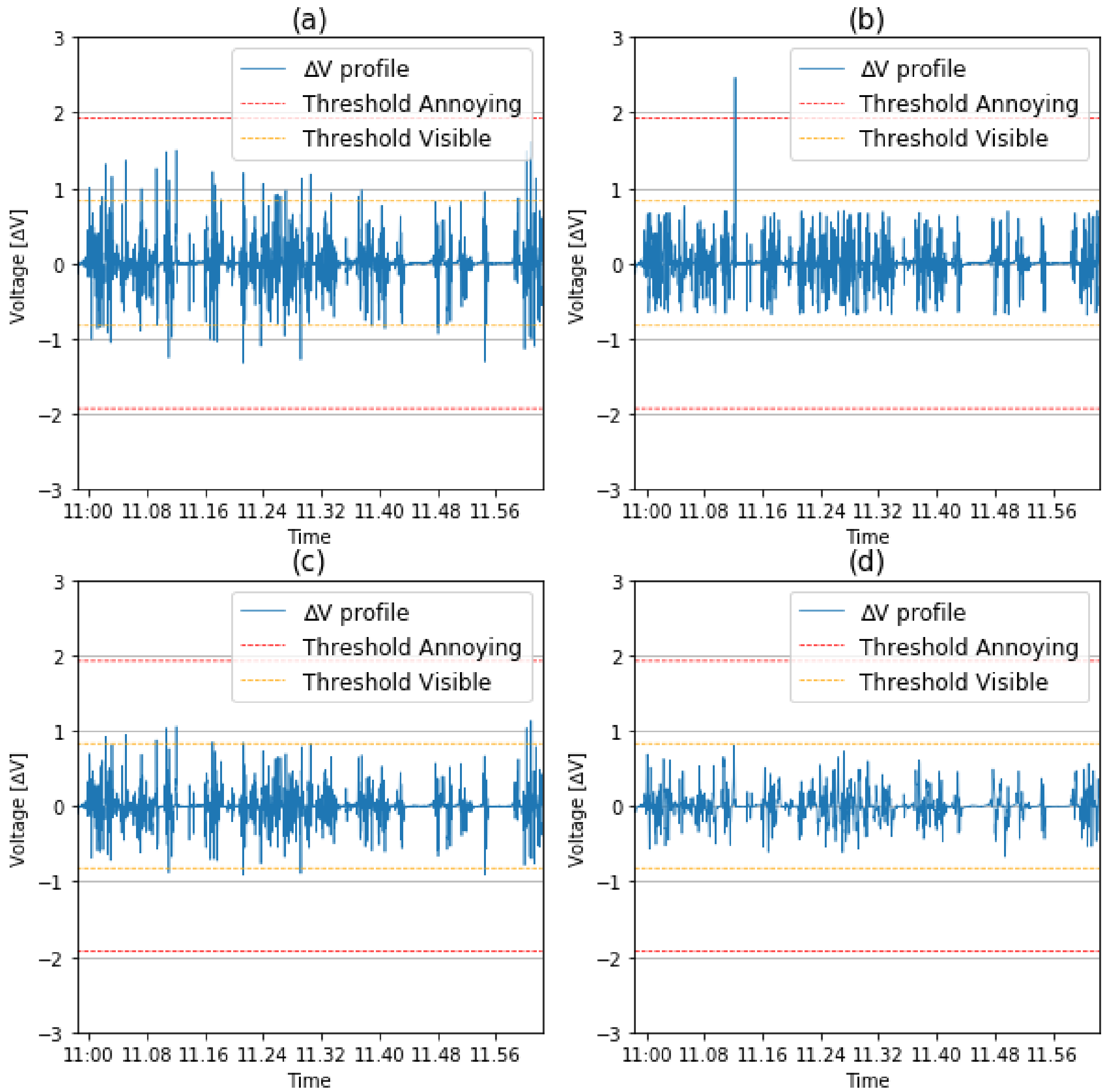

Figure 32: a) Voltage fluctuations 40% PV scenario 11:00-12.00 – no interference b) Voltage fluctuations 40% PV scenario 11:00-12.00 – curtailment c) Voltage fluctuations 40% PV scenario 11:00-12.00 – grid reinforcement d) Voltage fluctuations 40% PV scenario 11:00-12.00 – supercapacitor

Figure 33a shows the situation without interference in the 70% PV scenario. Similarly to the 100% PV scenario and the 40% PV scenario, the grid reinforcement option (Figure 33c) shows similar results, but to less fluctuating than the situation without grid reinforcement (Figure 33a). Comparing Figure 33b to Figure 32b shows that in the 70% PV scenario there are much more outliers in the voltage fluctuation profile, which is most likely a result from the increased installed solar PV systems. Comparing Figure 33d to the other Figures 33b and 33c shows that the supercapacitor option is the best option for voltage flicker mitigation in this scenario. It is more clearly the most suitable option than in the 40% PV scenario.

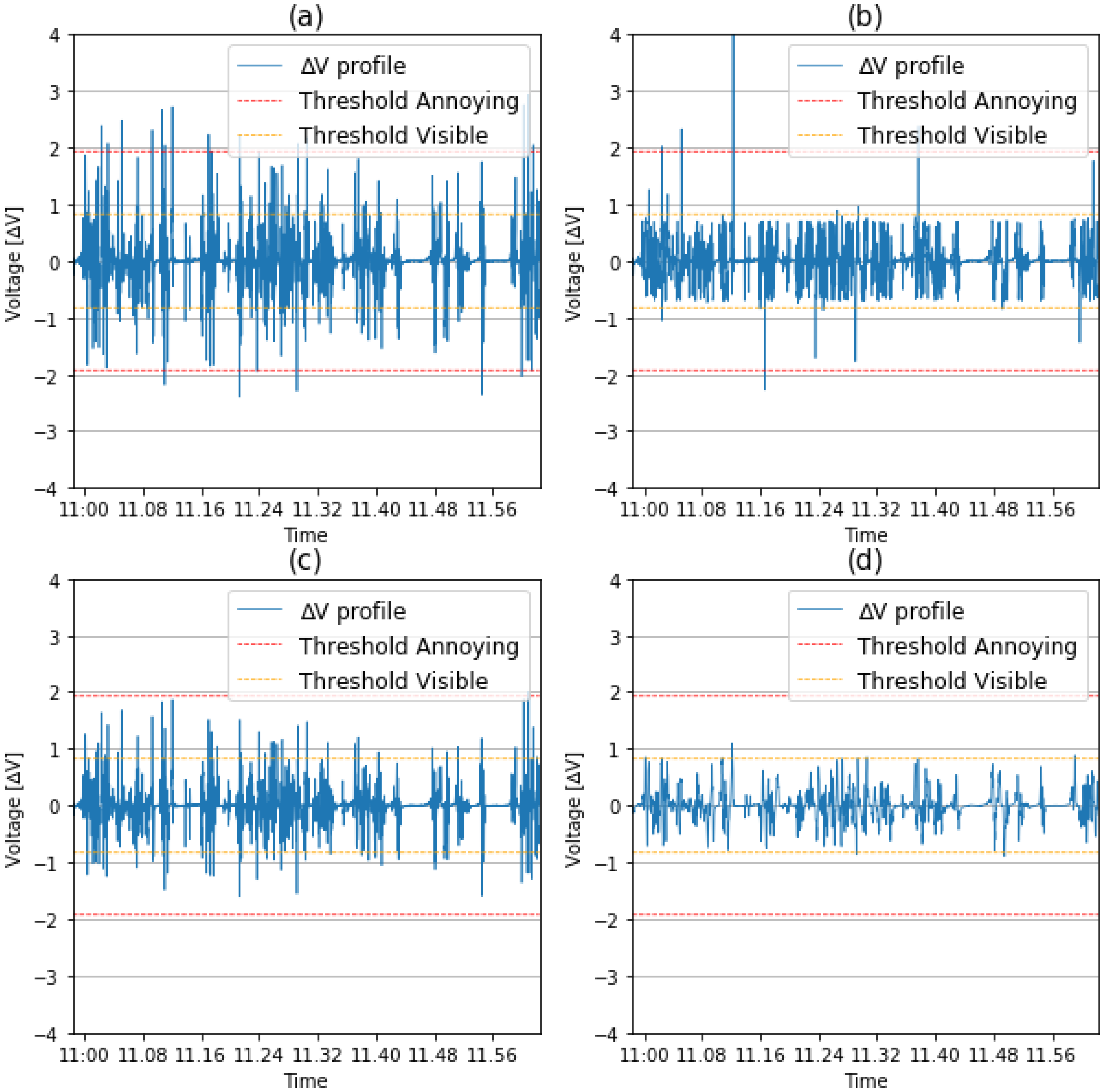

Figure 33: a) Voltage fluctuations 70% PV scenario 11:00-12.00 – no interference b) Voltage fluctuations 70% PV scenario 11:00-12.00 – curtailment c) Voltage fluctuations 70% PV scenario 11:00-12.00 – grid reinforcement d) Voltage fluctuations 70% PV scenario 11:00-12.00 – supercapacitor