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Grid integration of solar PV for multi-apartment buildings

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ABSTRACT

Multiple studies show that large installations of rooftop solar PV in residential low voltage grids, typically with many single family dwellings, may cause overvoltage issues during mid-day when local consumption is low and solar PV electricity generation high. Different so-called smart grid technologies, which often requires additional control, communication and monitoring equipment have been suggested to alleviate these and related problems. In this paper, solar PV integration is studied in the context of multi-apartment buildings where the rooftop potential is significant. To this end, the medium voltage grids of two multi-apartment areas, Bärnstenen and Alabastern in Vaxjö, Sweden are used as study cases. For these areas, it is found that active smart grid control or the introduction of new controllable load is not required. This finding applies to cases with very large solar PV installations corresponding to full coverage of the available rooftops and an annual yield corresponding to about eight times the annual electricity consumption. The conclusion is that multi-apartment residential areas may be ideally suited for large-scale solar PV installations without the need for smart grid infrastructure. These findings are contrary to, but not in disagreement with previous findings for low voltage residential grids.

Keywords:

Smart grid;
Solar PV;
Multi-apartment buildings;
Voltage control;
Medium voltage grid;

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1. Introduction

The electrical grid delivers electricity from generation stations to the end consumer. This grid is mainly composed of four sub-systems at different voltage levels. The extra-high-voltage (EHV) transmission grid with voltage levels ranging from 265 kV and upwards contain large-scale power plants such as coal, nuclear or hydro-electric with capacities of several hundred MW. Individual assets such as large wind turbines or energy intensive factories are typically connected to the high-voltage (HV) transmission grid with voltage levels ranging from 110 kV and upwards. The medium voltage (MV) and low voltage (LV) grids are typically referred to as the distribution grid. Here, the voltage levels range between 1kV to 35 kV in the MV grid and below 1kV in the LV grid. The distribution grid is most commonly the largest and most complex subsystem with consumption assest as super markets, residential areas, city networks and could possible include production assests as small scale solar and wind farms. The electrical grid is most commonly referring to the interconnected transmission system with a clear separation between the producers and consumers and by this only allowing for a unidirectional power flow. On the other hand, a smart grid allows for a bi-directional power flow where the consumers as well deliver energy to the grid [1]. According to the Modern Grid Initiative, smart grids are expected to sustain seven principal grid characteristics as, e.g., being self-healing, attack resistant or customer interaction allowing [2]. Due to the complexity of LV distribution grids, researchers have emphasized this subsystem. Here, we focus on the MV distribution subsystem.

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Smart Grid systems introduce a modern way of distributing electricity from energy producers to consumers. It also introduces a variety of different challenges at the power generation, transmission and distribution subsystems. In this work, we investigate the possibilities of covering the electricity demand from multi-apartment residential areas by installing solar PV panels on their rooftops. The question that is answered is to which extent the already existing electricity network is able to withstand the extra load forced into the grid by the PV panels. Due to large imbalances between the power production and consumption, these might cause over and under voltage issues.

In order to mitigate climate change, the share of rooftop-installed solar PV panels have shown to be important as discussed in e.g. [3]. A case study for Sydney, Melbourne shows that privately owned PV panels and storage can reduce the grid electricity import by up to 96% in summer time and shortfalls will occur in winter time [4]. A study case for Geneva shows high relevance of PV panels situated on rooftops and solar thermal potential for the urban electricity system [5]. These technologies may cause voltage issues and several studies have considered different approaches to balance these in LV grids. A systematic review on this topic is conducted in, e.g., [6] where smart metering is shown to be crucial as it provides necessary voltage information from both the supplier and consumer in order to provide timely control. Other research showed that assets such as electric vehicles have the ability of providing voltage support on the LV grid [7]. On the other hand, electric vehicles may also cause challenges for the LV distribution grid [8]. A control framework for voltage support has been provided by using agent-based technologies [9]. A MATLAB based simulation framework for verifying voltage control approaches implements flexible assets in order to ensure voltage stability [10]. The voltage control issues have been investigated for a number of LV networks, e.g., [11–14]. Apart from the technical aspects it is proposed that social aspects should be taken into consideration when designing electricity networks on urban level [15]. The main conclusion is that voltage instabilities are particularly likely to occur for the following two reasons: i) Since the voltage level is low (typically 400 V), the voltage increase required to inject a certain amount of power will be relatively large. ii) In low voltage grids, individual consumers and producers are usually connected in series along a radial single line starting from the transformer station. This means that imbalances can accumulate along the line. To the best of our knowledge, such studies are not available for the MV distribution grid. The reason for this may be due to the high voltage capacities in these networks and less complex network topologies. However, the lack of studies makes it hard to document the advantages of adding, e.g., renewable generation in the MV grid instead of the LV grid.

The voltage instability in LV grids can happen during mid-day when solar power is injected into the grid simultaneously from a high number of installations because production exceeds local consumption. This means that all positively (or negatively) accumulated voltage differences may cause overvoltage (or undervoltage) issues in the part furthest away from the transformer station. In its nature, solar power production is nearly perfectly synchronized in a small area, so overvoltage may occur when production peaks. In a similar way, electric vehicles (EVs) are anticipated to cause undervoltage issues if a high number are connected simultaneously, e.g., after work hours, in the same grid, see e.g., [8–10]. Different so-called smart grid technologies have been suggested to alleviate these and related problems. The technologies include: Control of the ratio between active and reactive power at some or all the connection points along the LV line; coordinated charging of batteries or EV's; and flexibility in the local consumption with the possibility of moving increasing or decreasing demand at certain times, e.g., moving refrigeration cycles. Typically these solutions require some form of communication and additional control and monitoring hardware to be installed in the network, as e.g., in [16–18].

In this study, the focus is primarily on distribution networks in residential areas with many multi-apartment buildings. While these buildings have an internal LV distribution network, the buildings will often be connected in parallel to the nearest MV transformer station. Furthermore, solar panels installed on the rooftop and other new installations, e.g. EV's, may also be connected in parallel to the buildings. As a consequence, voltage differences at LV does not accumulate but are instead averaged between all parallel connections at the transformer station. The setup reduces the chance of overvoltage in the LV grid and increases the ability of centralize control at the transformer station.

In a large multi-apartment residential area several MV-to-LV transformer stations will be connected in a MV distribution network, and if solar panels were installed on all buildings, and connected directly to the MV-LV transformers, it would be natural to expect overvoltage issues in the MV grid similar to those identified for LV grids. However, since the voltage level is much higher, typically 20 kV, the same amount of power injected will cause a much lower voltage increase at MV compared to LV. In addition, the individual transformers in a MV grid are typically not connected in series but rather in loops. These reduce the chance of voltage differences accumulating and causing overvoltage (or undervoltage) issues. Finally, rooftop area per dwelling is typically lower for multi-apartment buildings as compared to single-family housing, and thus the potential for rooftop solar installations is relatively smaller. Consumption per dwelling may also be lower. This is illustrated with examples in Table 1.

In summary, the paper explores two case studies where large amounts of solar PV are installed on multi-apartment buildings located in existing distribution grids. The main objective is to highlight the qualitative and quantitative differences between connecting the installations at respectively LV or MV. In this context particular attention is brought to handling typical issues of overvoltage using new smart grid technology. In this analysis we use four different cases: no PV panels installed, peak matching, energy matching and full roof coverage.

1.1. Structure of the paper

The remainder of this paper is structured in the following way. In Section 2, the study cases and scenarios are outlined. Section 3 describes the methodology that is used to analyse the electricity grid. The results are described and discussed in Section 4, and Section 5 summarises and concludes the paper.

Table 1: Scaling of consumption with rooftop area for the two multi-apartment areas Bärnstenen and Alabastern in Växjö. A typical number for a suburban single–family house with an annual consumption of 6000 kWh/year [19] and a 6 kWp solar PV installation (*about 40 m^2 of the roof is typically used for PV installations) [20] is also shown.

Residential area	Consumption per rooftop area [$^{kwh}/m^2$]	Rooftop area per dwelling [m^2]
Bärnstenen	33	40
Alabastern	26	37
Suburban	150	40*

2. Study cases and scenarios

The following four different scenarios with increasing amounts of solar PV installations are analysed:

- **No PV:** In this reference scenario, the local grid is modelled as it currently is with no solar PV installations.
- **Peak matching:** The roof is partially covered with PV. The degree of coverage is determined such that all generated electricity can potentially be used locally, i.e. annual peak production equals the demand when it occurs.
- **Energy matching:** The degree of roof coverage is determined such that the annual electricity yield from solar PV matches the total annual consumption.
- **Full roof coverage:** The roof is fully covered with solar PV.

Two sets of calculations are carried out; where first the scenarios are applied to a single building in the network and then to all buildings, e.g. one building with full roof coverage or all buildings with full roof coverage.

The two multi-apartment residential areas Bärnstenen and Alabastern in the city of Växjö, Sweden have been selected as study cases. In these areas large-scale demonstration of PVT panels will be carried out over the coming years as part of the READY project. Similar demonstration projects will be carried out at Ringgaarden District 20 and District 21 in Aarhus, Denmark [21].

In the following sections, the study cases and the data used in the studies are described in more detail. The study cases and scenarios are summarized in Table 2.

2.1. Distribution grid topology for Bärnstenen

Figure 2 shows the residential area of Bärnstenen including the electrical grid. The latter is illustrated schematically in Figure 1, panel (a) including the bus numbering used in this study. Bus 2 represents the connection to the high-voltage grid at Bus 1 and consumption from the multi-apartment buildings is aggregated on Bus 3 to 9.

Figure 1, panel (b) shows a special modification of the grid where the two multi-apartment buildings at Bus 9 are

Table 2: Summary of the study cases in Bärnstenen and Alabastern

		Base case	Peak matching	Energy matching	Full roof coverage
Bärnstenen	Area [m^2]:	0	75	309	2086
Single building with PVT	Capacity [kWp]:	0	52	215	1,449
Consumption: 91.2 MWh/yr	Production [$^{MWh}/_{yr}$]:	0	22.10	91.30	616
Bärnstenen	Area [m^2]:	0	7×75	1,485	12,502
All buildings with PVT	Capacity [kWp]:	0	365	1,03	8,682
Consumption: 439 MWh/yr	Production [$^{MWh}/_{yr}$]:	0	155	438	3,694
Alabastern	Area [m^2]:	0	75	242	1,482
Single building with PVT	Capacity [kWp]:	0	52	167	1,022
Consumption: 71.6 MWh/yr	Production [$^{MWh}/_{yr}$]:	0	22.1	71.5	436
Alabastern	Area [m^2]:	0	8×75	1,338	9,866
All buildings with PVT	Capacity [kWp]:	0	414	923	6,804
Consumption: 395 MWh/yr	Production [$^{MWh}/_{yr}$]:	0	177	395	2,915

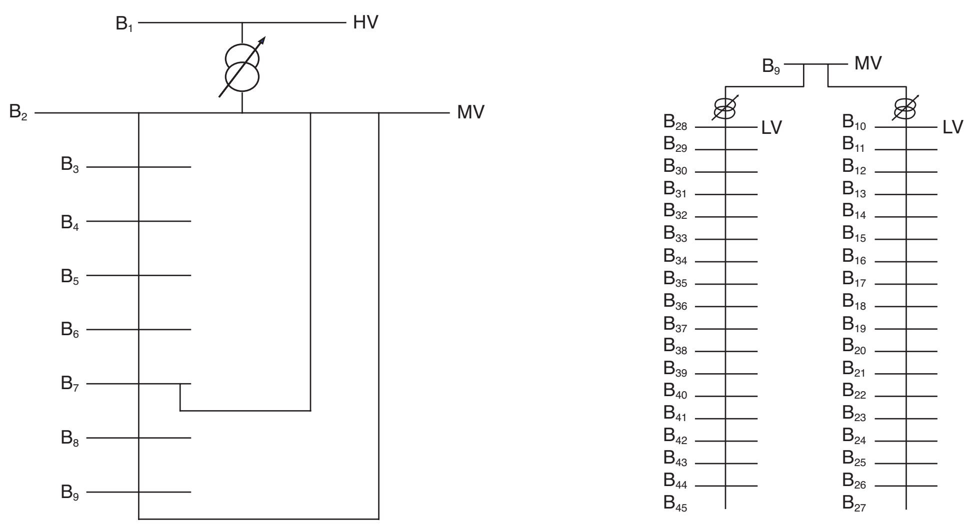

Figure 1: Panel (a), left figure: Model topology for the distribution grid in Bärnstenen. All multi-apartment buildings are connected by a direct line to the nearest MV-to-LV transformer. Panel (b), right figure: Model topology used in the special case where each of the two multi-apartment buildings located at Bus 9 are replaced by 18 individual houses connected in a standard LV configuration

replaced with 18 individual dwellings each (corresponding to the number of apartments). These are connected in two parallel LV lines. This modification is also modelled and results will be discussed later in the text.

2.2. Distribution grid topology for Alabastern

In Figure 3 the residential area for Alabastern is shown. The grid topology and bus numbering is illustrated schematically in Figure 4.

This electricity network is slightly different from the one in Bärnstenen as it is connected to the high-voltage grid in two locations at Bus 4 and 12. Consumption is introduced from bus 5 to bus 11 and bus 13 based on annual consumption of the individual buildings. In Figure 3, the upper right building is attached to Bus 4 through a low voltage cable. However, in the model this building has been aggregated into Bus 5.

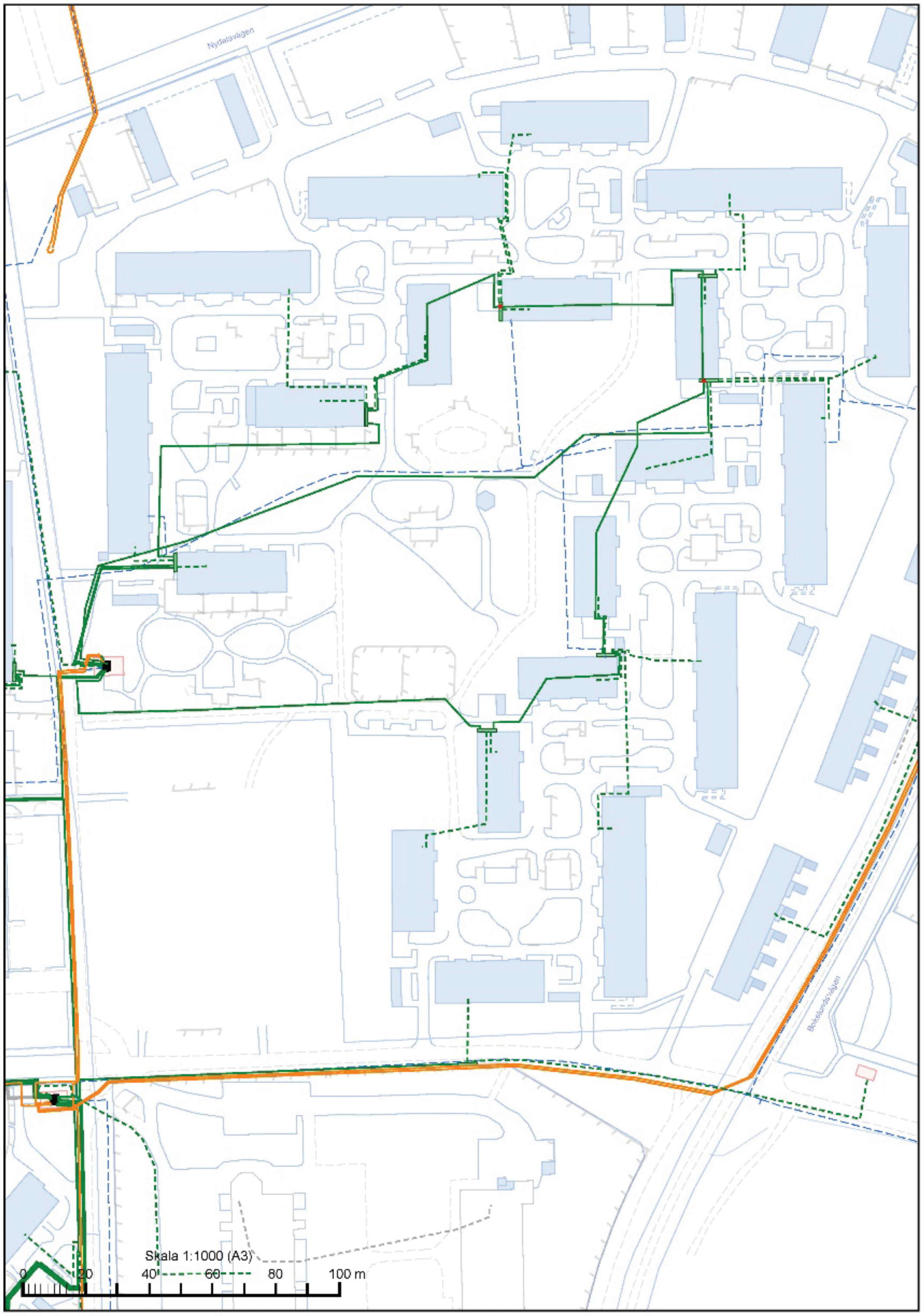

Figure 2: The residential area of Bärnstenen. Only the medium voltage lines (solid green) and the local HV-to-MV transformer are included in the network model. Each individual building is connected to a MV-to-LV transformer via a single LV line (dashed green) and the electrical output from the PVT panels is assumed to flow on these. Also shown is a small part of the local high voltage grid (solid orange)

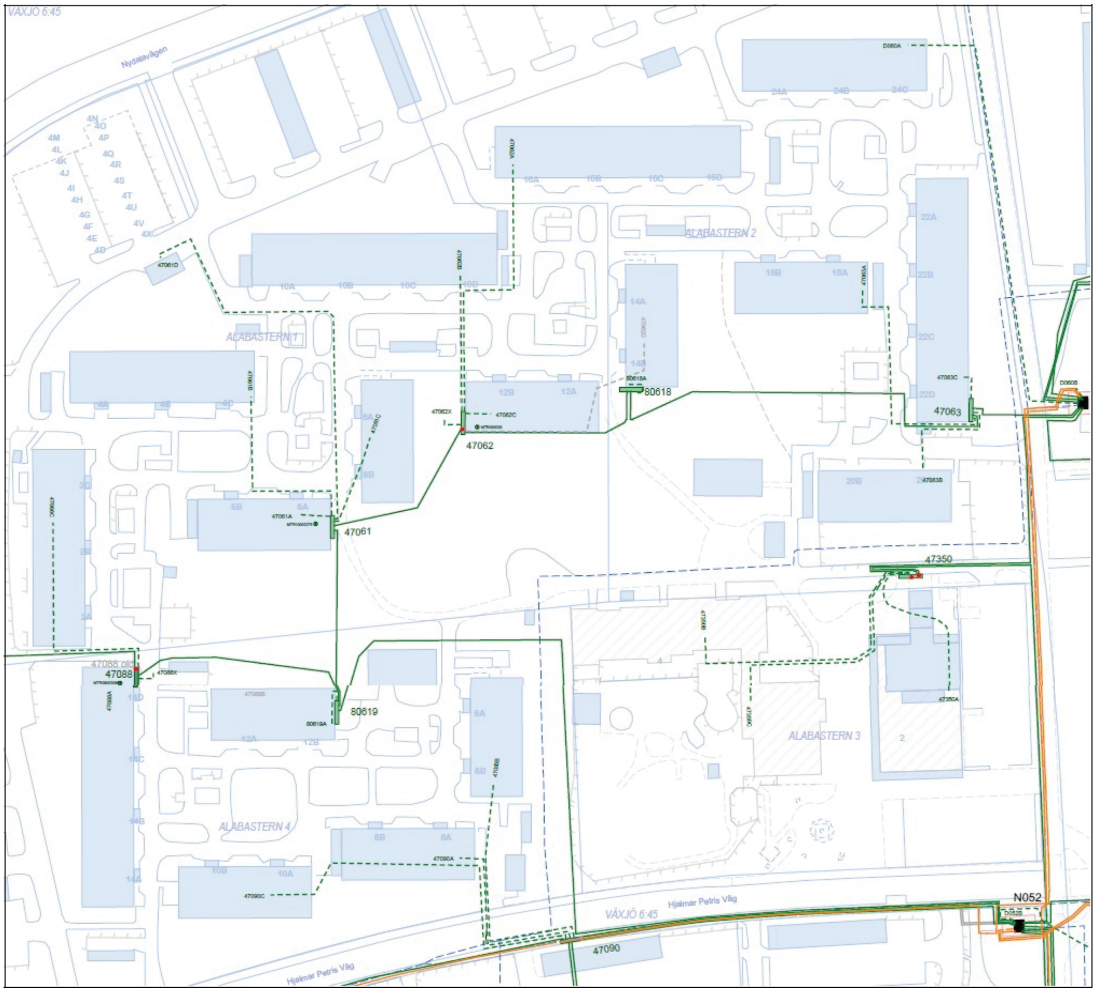

Figure 3: The residential area Alabastern. Only the medium voltage lines (solid green) and the local HV-to-MV transformer are included in the network model. Each individual building is connected to a MV-to-LV transformer via a single LV line (dashed green) and the electrical output from the PVT panels is assumed to flow on these. Also shown is a small part of the local high voltage grid (solid orange)

2.3. Electricity consumption profiles and distribution grid data

The electrical distribution grid topologies for the areas Alabastern and Barnstenen have been provided by the executive office of Växjö. CA Fastigheter AB has provided data for the annual consumption of electricity for each of the multi-apartment buildings in the areas.

In order to obtain reasonable electricity consumption profiles for each of the multi-apartment buildings, hourly consumption profiles for multi-apartment buildings have been obtained from [22]. This data has then been scaled linearly to match the annual consumption for each individual building, and a random variation with an amplitude of +/-10% has been added for each hour to emulate variations in the demand between buildings.

3. Methodology and model description

Dynamic modelling of the electrical distribution grid where the solar PV panels are present is carried out using a direct adaptation of the open source framework DiSC presented in [10]. DiSC can be used to model combinations of low and medium voltage grids connected to one or more high-voltage transformer stations. It allows for the introduction of new smart grid technologies. It is particular useful for identification of overvoltage issues and for analysing the possible

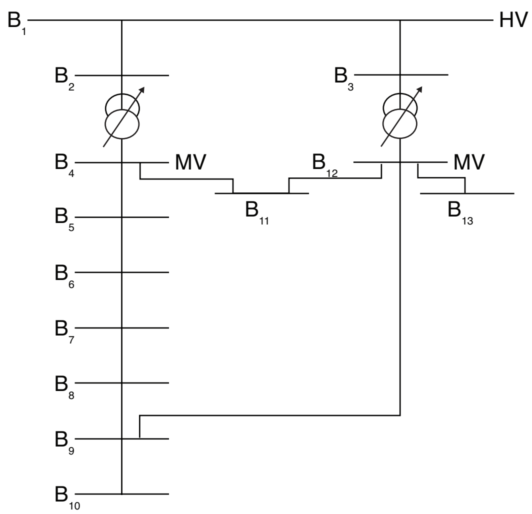

Figure 4: Model topology of the distribution grid in Alabastern. Note that the MV grid is connected to the high-voltage grid at two locations

benefits of intelligent control of distributed devices. Below, a brief description that focuses on the parts of the framework used in this study is presented. Additional information can be found in [10] and references therein.

3.1. Electrical grid

A Newton-Rapson power flow solver is used to determine the non-linear currents and voltages differences between the individual busses in the network. To reduce the complexity of the problem a balanced three-phase system is assumed in the MV and LV parts of the grid. Furthermore, the high-voltage grid is assumed to be capable of delivering any required power, which means that the frequency is kept constant. This allows for focusing on voltage control issues, which are handled at the bus where they occur.

In all of the scenarios the specific cable impedance is set to a standard value of 0.1 + i0.08 ohm/km [10]. The cable length is chosen according to the actual length in the network. The interplay between these variables needs to be chosen carefully or else there would be converge problems in the network. In the MV range the reactance is the most important factor while the cable resistance becomes important when LV networks are modelled.

In the analysis below, we define the occurrence of over and under voltage issues, when the 10 minute mean value of the supply voltage either exceeds or lags the nominal voltage by at least 10%. Defining the voltage variability this way is in correspondence with a former study on the voltage characteristics of public distribution systems [23].

3.2. Photovoltaic system model

Because the primary concern of this study is the dynamic effects that solar PV panels have on the electricity distribution network, and not the exact energy production, a simplified model with a focus on the system behaviour at short time scales is applied. This model combines a solar irradiance model based on a stochastic Markov process to emulate variations in cloud cover with a simple electrical model of the panel. The model is described briefly below.

A common solar panel, made of GaAs or Si, losses approximately 0.06% of its efficiency for every degree of increased temperature [24]. For this reason, it is assumed that each panel is independent of the ambient temperature. This small difference in the efficiency does not have any great influence on a medium voltage network and thereby will not alter the results of this study.

Furthermore, each PV panel is assumed to be placed horizontal to the Earth's surface. The system is defined by the area it covers A in m^2 and the efficiency of its cells n. The produced power p in Watt is given as

$$p = \begin{cases} p_{rated} & if\, \eta A I_{solar} \geq p_{rated} \\ \eta A I_{solar} & if\, \eta A I_{solar} > p_{rated} \\ 0 & otherwise \end{cases}$$

Where p_{rated} denotes the total installed capacity of the panel.

The total solar irradiance I_{solar} consists of beam irradiance I_{beam} and diffusive irradiance I_{irr}. Beam irradiance is only present when the sun is shining from a clear sky, while the diffusive irradiance consists of irradiance emanating from the cloud free part of the sky and irradiance emanating from the cloud covered part of the sky.

3.3. Active and reactive control interface

Some inverters are able to control the relationship between active and reactive power they deliver to the electricity grid. By doing so in a coordinated (smart) way, the inverter can partake in the control of the local electricity grid.

The active power can be controlled in two ways where the first is by derating the power. Here the maximum power of the solar power plant p_{rated} is limited to a value $p_{rated} - \Delta p_{lim}$ where $\Delta p_{lim} > 0$ is a control variable that determines how much the power output should be derated. The other way of controlling the active power is to make a change in it directly. This means that the active power can be curtailed by an amount of Δp_{ref}. The modified produced power is then:

$$p = \begin{cases} p_{rated} - \Delta p_{lim} + \Delta p_{ref} & if\, \eta A I_{solar} \geq p_{rated} \\ \eta A I_{solar} + \Delta p_{ref} & if\, \eta A I_{solar} < p_{rated} \\ 0 & otherwise \end{cases}$$

where it is assumed that $0 \leq p_{rated} - \Delta p_{lim} + \Delta p_{ref} \leq \eta A I_{solar}$.

The reactive power reference can be controlled in three different modes:

$$qref = \begin{cases} \frac{p_{mes}}{q_{ref}} \tan\left(\cos^{-1}(\delta)\right) & if\, mode = 0 \\ & if\, mode = 1 \\ \alpha\left(v_{ref}, v_{mes}\right) & if\, mode = 2 \end{cases}$$

mode = 0 corresponds to a constant power factor, mode = 1 corresponds to a reference following on reactive power and mode = 2 corresponds to voltage control. $\overline{qref}$ is the reactive power reference, δ is the desired power factor, v_{ref} is a reference voltage, v_{mes} is the measured voltage at the connection point and α is determined as:

$$\alpha\left(v_{ref}, v_{mes}\right) = \frac{2s_{max}}{\left(v_{max} - v_{min}\right)}\left(v_{mes} - v_{ref}\right)$$

where s_{max} is the maximum apparent power and v_{max} and v_{mes} is the maximum and minimum allowable voltage values, respectively.

The reactive power is limited by a maximum apparent power s_{max} of the converter and the reactive power output is

$$q = \begin{cases} q_{ref} & if \left|q_{ref}\right| \leq q_{max}(p) \\ sign\,(q_{ref})\, q_{max}(p) & otherwise \end{cases}$$

Where $q_{max}(p) = \sqrt{s_{max}^2 - p^2}$ and the apparent power is $s = \sqrt{q^2 + p^2}$.

4. Model results and discussion

Results have been calculated for all the study cases presented in Table 2, and the maximum overvoltages that have been detected during the one-year model period are summarised in Table 3.

Table 3: Maximum overvoltages observed during the one-year study period

		Base case [V]	Summer peak match [V]	Annual energy match [V]	All roof covered [V]
Bärnstenen Single building with PVT Consumption: 91.2 MWh/yr	Maximum overvoltage:	0	0	5	45
Bärnstenen All buildings with PVT Consumption: 439 MWh/yr	Maximum overvoltage:	0	12	33	274
Alabastern Single building with PVT Consumption: 71.6 MWh/yr	Maximum overvoltage:	0	0	2	16
Alabastern All buildings with PVT Consumption: 395 MWh/yr	Maximum overvoltage:	0	7	15	110

It can be seen that both areas Bärnstenen and Alabastern generally yield similar results with overvoltage well below critical limits (about 10%), even for the scenarios where all roofs are fully covered with solar panels. Overvoltage at 274 V and 110 V for Bärnstenen and Alabastern, respectively, has no significance on a medium voltage grid at 2000 V. The maximum overvoltage scales linearly with the installed solar capacity with about 0.032 V/kWp in Bärnstenen and 0.016 V/kWp in Alabastern. This difference can be attributed to the differences in network topology, and mainly to the presence of two high-voltage transformers in Alabastern and only one in Bärnstenen. In absolute terms, over voltages ranging from about 5 to 274 V are observed. In a 20 kV MV grid, these levels are fully acceptable, but in a 400 V LV grid many of the scenarios would not be acceptable.

As illustrated by Figure 5 and Figure 6, voltage levels are close to constant throughout the networks. This is contrary to the behaviour in many LV networks where voltage differences from solar power injections accumulate towards the far end of the line. This accumulation arises due to the ratio of the injected PV power versus local loads at each node.

4.1 Multi-apartment vs singly family housing

The difference between a typical LV grid of single-family houses and multi-apartment dwellings has been explored in modification of the distribution grid for the Bärnstenen area. The modification is shown in

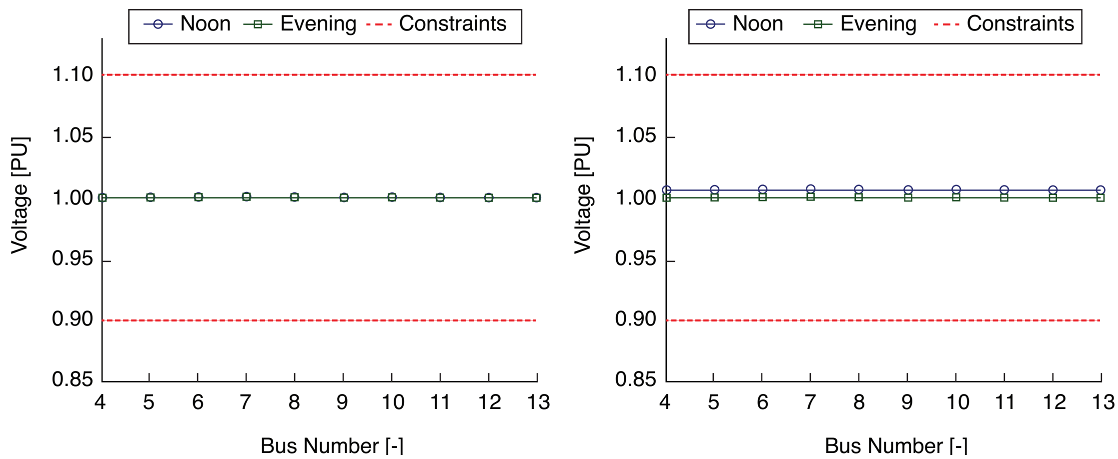

Figure 5: Voltage at the buses in the medium voltage grid for the residential area Alabastern. Panel (a) shows results for the base case with no PV installations. Panel (b) shows the corresponding data for the case where all roof-tops are entirely covered with PV panels

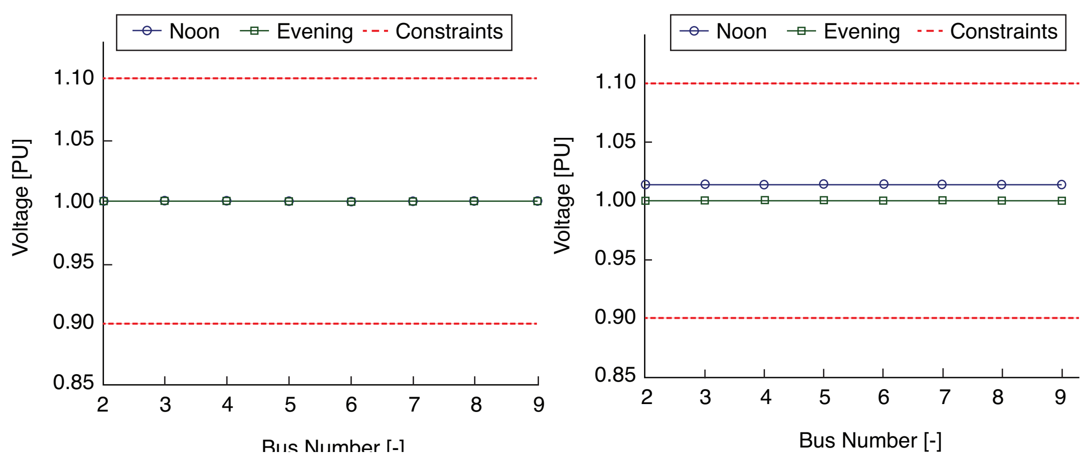

Figure 6: Voltage at the buses in the medium voltage grid for the residential area Bärnstenen. Panel (a) shows results for the base case with no PV installations. Panel (b) shows the corresponding data for the case where all roof-tops are entirely covered with PV panels

Figure 1b, where two multi-apartment buildings have been replaced by 2 times 18 individual houses connected in series. Each of these has then been assigned a proportional share of both consumption and solar PV installations.

In Figure 7, the results of these simulations are presented. Panel (a) shows results for the case where annual solar production is matched to annual consumption, and Panel (b) shows the case where the total solar installations corresponds to full coverage of the roof-tops of the original multi-apartment buildings. In the first case, overvoltages in the modified grid remain within acceptable limits. However, in the latter case, an overvoltage of about 200% occurs. This is far beyond any acceptable limit.

4.2. Smart voltage control

The DiSC modelling framework allows for active control of reactive and active power at the solar PV inverter. Since all voltages remained well within acceptable limits in all the main model scenarios, activating this control makes no noticeable difference.

In the modified grid, discussed above, active control does reduce overvoltage by 20 V at bus 28 as seen in Table 4. However, in the extreme cases modelled here, the effect is nowhere near large enough to reduce overvoltage to within acceptable limits as seen in Figure 8 and Table 4. Instead, severe curtailment of the solar energy must be applied if the overvoltage issues were to be avoided. Preliminary studies show that the presence of large batteries in the LV grid could alleviate the overvoltage problems. This finding is consistent with that of [10].

5. Summary and conclusion

Integration of solar PV panels has been studied in the two multi-apartment distribution grids Bärnstenen and Alabastern in Växjö. The study includes solar

Table 4: Maximum overvoltage at busses with and without voltage control

Bus number	Overvoltage without control in V	Overvoltage with control in V
10	3.10	–0.06
11	23.17	17.64
12	41.84	34.26
13	59.18	49.78
14	75.21	64.22
15	89.96	77.56
16	103.50	89.85
17	115.81	101.08
18	126.93	111.28
19	136.87	120.44
20	145.69	128.56
21	153.36	135.66
22	159.91	141.74
23	165.36	146.79
24	169.36	150.83
25	172.95	153.86
26	175.11	155.88
27	176.19	156.88
28	176.19	156.88

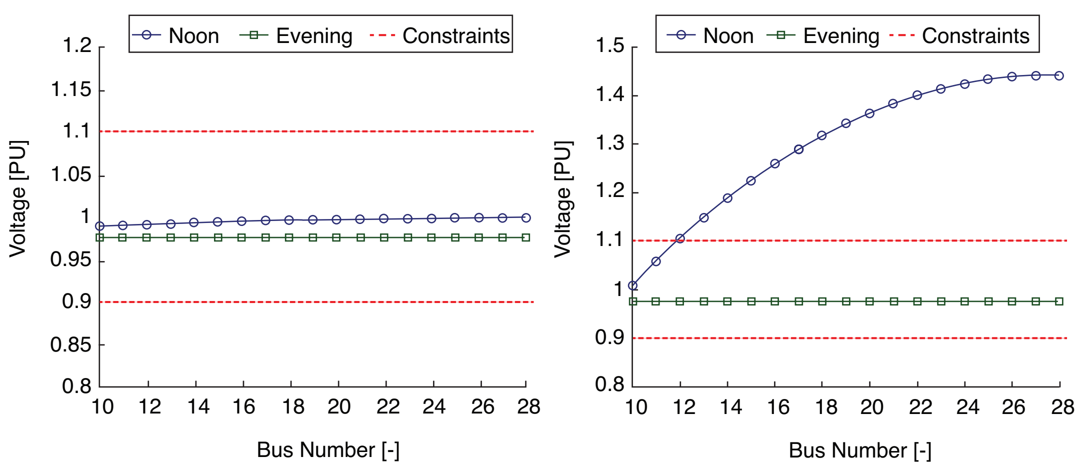

Figure 7: Special cases where the two multi-apartment buildings connected to Bus 9 in the Bärnstenen distribution grid are replaced with individual dwellings. These are connected with LV lines as shown in Figure 1b and consumption as well as solar panels are distributed evenly between each of the LV busses. Panel (a) shows the voltage at each LV bus for the case where annual PV production match annual demand. Panel (b) shows the situation for the case where the total PV installation would cover the entire roof of the original multi-apartment buildings.

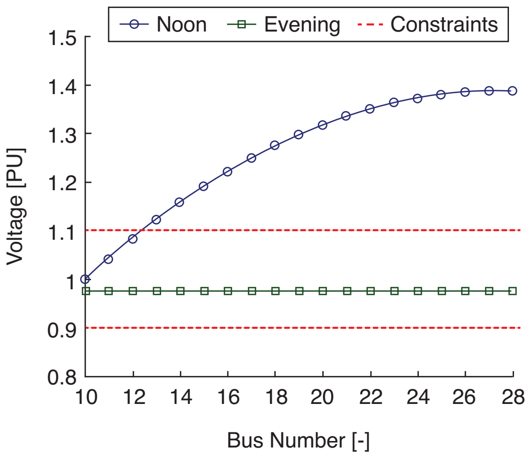

Figure 8: Voltage at the busses when voltage control (mode 2) has been applied on reactive power

installations ranging up to full roof coverage of all the buildings in the areas. This corresponds to a solar installation that generates about eight times as much electricity as is consumed in the buildings on an annual basis.

During the summer period, this results in large amounts of solar power being injected in distribution grid, which may cause overvoltage issues. However, it is found that the grid topology in the studied multi-apartment residential areas can, in fact, handle these large solar PV installations without overvoltage issues. It is also shown that this would not have been the case if the same installations had been distributed on single-family dwellings.

The analysis presented above clearly indicates that the distribution grids in the two multi-apartment areas Bärnstenen and Alabastern allow for very large solar PV installations, and active control or the introduction of new controllable load from e.g. EV's is not required.

These findings are contrary, but not in disagreement with a number of studies of typical single-family housing residential LV distribution grids [10–14]. Mainly because solar panels can be connected in parallel to the combined demand from each building and not as a number of independent units along the LV line. Thus, overvoltage issues are transferred to the MV level where their relative impact is much lower.

The consequence is that multi-apartment residential areas may be ideally suited for large-scale solar PV installations. Although many existing LV grids can in fact handle installations with an annual energy yield that corresponds to the annual electricity consumption [12].

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