Effects of solar PV installations and solar inverter reactive power control on distribution network losses on Finnish rural areas

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Effects of solar PV installations and solar inverter reactive power control on distribution network losses on Finnish rural areas

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***Abstract*—Energy transition is reshaping energy systems and affecting loading of electricity distribution networks significantly. Household customers are investing in solar PV systems to locally produce electricity for their own demand and to sell energy to the distribution grid. Solar PV systems can cause voltage rise problems or overloading of secondary transformers. Voltage rise challenges can be moderated with reactive power control of solar PV inverters. On the other hand, reactive power consumption on solar PV inverters affects the distribution network losses.**

This paper focuses on studying how the increasing amount of distributed solar PV capacity will affect the distribution network losses in Finnish conditions. Secondly, it is studied what kind of impact the solar inverter reactive power control will have on the losses.

***Index Terms*—solar photovoltaics, network losses, electricity distribution, renewable energy**

I. INTRODUCTION

Electricity distribution grids are facing significant fast-paced developments due to energy transition. Distributed renewable energy production units are becoming more and more popular. Solar photovoltaics (PVs) are installed in large-scale production units as well as household rooftop systems.

Distributed solar PV systems affect the electricity distribution network loads, voltages and losses. Wide-spread solar PV systems can cause over-voltage problems to the distribution grids, but these challenges can be to an extent avoided by reactive power control [1], [2]. Limiting the voltage rise with reactive power control of solar PV inverters increases the risks of overloading secondary transformers and can have an effect on distribution network losses. Solar PV inverter reactive power control settings are set when the system is installed, and thus it is important to understand what kind of effects the chosen reactive power control method has. Changing the settings after installation of the system is rare.

Effects of distributed solar PV systems on distribution network losses have been previously studied in publications such as [3], [4]. The effects can vary depending on the operating conditions and the needed reactive power control settings can be different. Thereby, it is essential to understand what are the effects in different operating environments.

This paper focuses on studying how the distribution network losses will develop with large penetrations of rooftop PV systems for Finnish household customers, and how this development might affect the costs of DSOs.

II. BACKGROUND OF THE STUDY

This section describes the operation environment and principles affecting the network dimensioning, and thereby network losses. In the Nordic conditions seasonal loads, low customer densities and summer-emphasized solar PV production curves can have effects on the development of distribution network losses.

A. Seasonal loads

In the Finnish electricity system seasonal variation of electricity demand is significant. The wintertime heating demand is covered to a large extent with electric heating solutions. However, the cooling demand during the summer is relatively low. Thus, the electricity demand is low during the summer while PV production is on its highest and during wintertime the demand is high and PV production is low or even zero at times when solar panels are covered with snow. Fig. 1 illustrates relative electricity demand on Finnish rural area primary substation on hourly basis during one year.

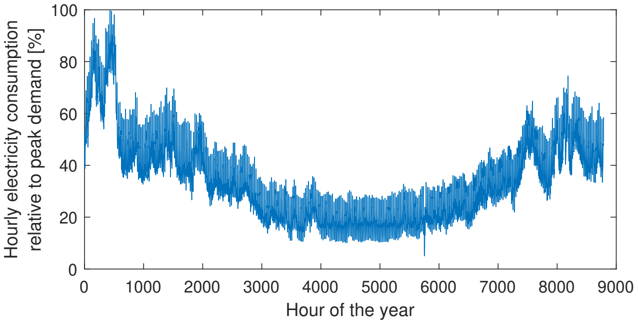

Figure 1. Relative electricity consumption during year 2016.

It is visible that the summertime load demand is significantly lower compared with the winter season demand. Fig. 2 demonstrates the PV production curve during the same year.

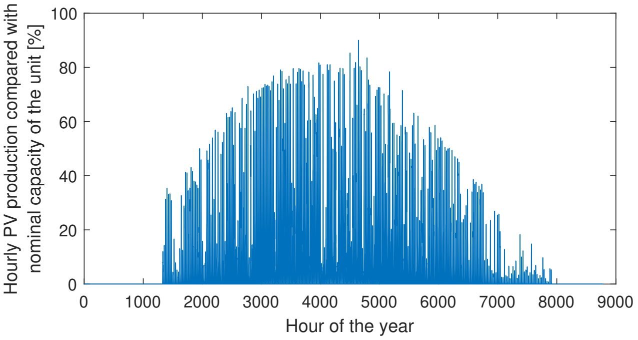

Figure 2. PV production curve on hourly data.

It can be seen that the solar PV production curve and electricity consumption curve are inversely proportional. Thereby, integration of solar PV systems on household customers' connections can cause a change in direction of current in the low-voltage networks, and thus potentially leads to voltage rise problems.

B. Distribution networks in Finland

Distribution networks in Finnish rural areas are typically radial medium-voltage (MV) feeders with only a few backup connections. Customer density is low and distances are long. The electric heating systems are relatively common, and the distribution networks are quite stiff due to wintertime load demand. In a stiff network changes in power have only minor effects to the customer connection voltages. The electrical safety regulations also affect the network dimensioning, because DSOs have to ensure a minimum of 250 A short-circuit current to connections with a typical main fuse size of 3x25 A [5]. The customer connections are mainly 3-phase connections with 3x25 A main fuses or higher for household customers.

The MV-line dimensioning can be relatively high capacity especially on lines that are dimensioned to act as a backup during primary substation transformer fault. Branch MV-lines are more typically dimensioned based on normal operation conditions. Thereby losses in the MV-lines are typically relatively low. Distribution networks in the rural areas have been typically built as an overhead line network, but the security of supply requirements have increased, and thus the rural area networks are partly renovated with underground cable networks. Underground cabling can be dimensioned with higher capacity than overhead lines because capacity strengthening afterwards is significantly more expensive.

C. Solar PV systems

The rate of solar PV installations in Finland has been lacking compared with the pace on a global level. This has been due to low subsidies available for household customers, relatively low electric energy prices, and relatively high costs of PV installation work. Fig. 3 illustrates the development of PV installation rates in Finland and globally.

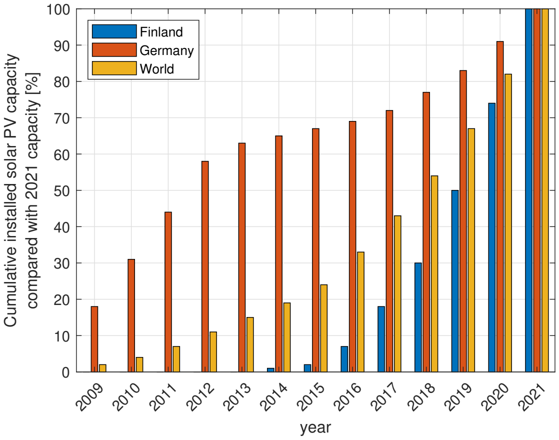

Figure 3. Development of installed solar PV capacity in Finland, in Germany and worldwidely [6]–[8].

It can be seen from the figure that the relative increase in installed solar PV capacity has been considerable during the past few years.

In Finland, the current grid dimensioning recommendations suggest reactive power control of solar PV inverters to not be utilized because sufficient analyses to define recommendable settings that would be suitable for all distribution system operators in Finland have not been made [9].

D. Electricity market price

During the year 2022 the Nordpool Spot prices have increased rapidly, which has improved the profitability of PV systems dramatically. Thereby, the demand for PV systems has also increased considerably and the capacities of installed PV systems have grown. Fig. 4 illustrates the development of electricity market prices during 2017–2022.

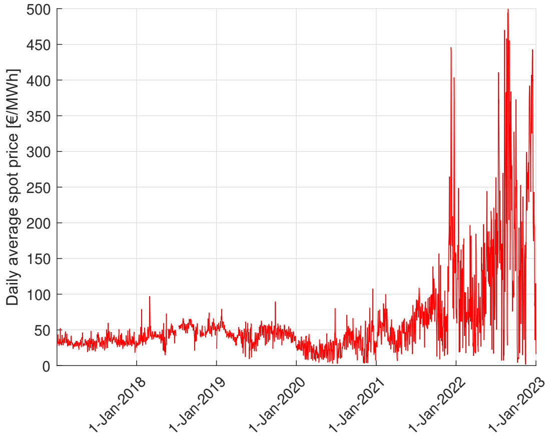

Figure 4. Daily averages of electricity spot price in Finland during 2017–2022 [10].

It is visible that spot prices have been steadily at an approximately 40–60 €/MWh level before the year 2021. Higher electricity market prices increase the importance of network costs for the DSO.

E. Network losses

Distribution network losses can be divided into no-load losses and on-load losses. No-load losses are mainly dependent on the distribution transformer dimensioning and type choices. Larger transformers have higher no-load losses, but lower on-load losses. These no-load losses can have a significant effect on the life-cycle costs of a distribution transformer.

The costs of distribution network losses are approximately 5–6% of total costs of a DSO in Finland [11], [12]. These estimates are made with cost data of DSOs from years 2018–2021. The DSO has to buy the energy wasted in the network losses from an electricity retailer. Thus, the cost of losses is dependent on the electricity price in addition to the amount of losses.

III. METHODOLOGY

The methodology used to analyze the network losses is described in this section. The methodology consists of four main parts: modeling of solar PV production, setting the solar PV scenario, executing power flow analysis for distribution networks, and analyzing the development of distribution network losses.

A. Solar PV production

Solar PV production was modeled based on metered values of a real solar PV system of LUT University located in south-eastern Finland. The production data was utilized on an hourly basis. The data was scaled down to equal household-scale customers PV installations. The production unit from which the data was acquired is installed facing south with tilt angle of 15° with no relevant shadings. In this study it was assumed that all solar PV panels are installed facing south. In practice, rooftops of customers' buildings may affect the direction of installation. On rural conditions customers have typically larger plot of land, and thus the solar PV panels can be installed ground mounted if their buildings' rooftops are not suitable for installation.

B. Scenarios

1) PV penetration: PV unit sizes were varied between 1–10 kWp. For the smallest customers, that have annual consumption lower than 2 MWh, the highest PV capacity was set to 3 kWp. PV penetration rate was varied between 25% and 100%.

2) Reactive power control: Reactive power control was simulated to be constant $\cos\phi$ absorbing reactive power from the distribution network.

C. Power flow calculation

Power flow analysis was carried out on a Matlab® backward-forward sweep load flow calculation model. The load flow was calculated for each hour of a year, and the network losses were compared on a yearly basis. Power factor of the electricity consumption was assumed to be $\cos\phi = 0.95_{\text{ind.}}$. MV lines were modeled with Π model to include the operating capacitance of the lines. Secondary substation transformers were modeled as a series impedance and no-load losses were set as constant loads in transformer nodes. Low-voltage lines were modeled as series impedances.

D. Analysis of network losses

Network losses were first analyzed without PV installations for every hour of a year. Then the PV adoption rate and installed PV sizes were varied, and the network losses were analyzed on an hourly level. The analyzed network losses included losses from low-voltage lines, secondary substation transformers and medium-voltage lines.

E. Costs of network losses

Costs of network losses are dependent on the DSO's contract with the electricity retailer from which it buys the energy. The price can be constant price or hourly spot price. In this paper it was assumed that DSOs would have spot market based contracts.

IV. CASE STUDY RESULTS

A case area study was performed for cases areas located in Finnish rural area. The case areas include four MV feeders, 281 km of MV lines, 240 secondary substations and 1424 customers. Distribution networks were modeled from customer connections to the primary substation level. Electricity consumption data used in this study was hourly AMR data of the customers. Customers' actual locations were unknown but the topological connection to the distribution network was known.

In this section results of the case study are presented. First, the profile of network losses with and without solar PV systems is studied.

A. Profile of network losses

Network losses are dependent on the electric current transferred through the network components, and thereby the consumption and production profiles of the customers play significant role in the profile of network losses. Fig. 5 illustrates how the profile of network losses develops during summer days with solar PVs installed.

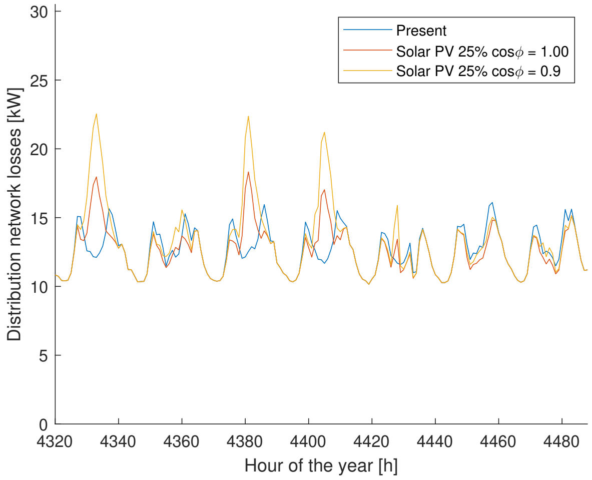

Figure 5. Development of profile of distribution network losses with PV installations.

It can be seen from the figure that distribution network losses increase when solar PV production is at its highest but the losses during evenings and mornings are more likely to decrease.

B. Development of network losses

Network losses were estimated with 25% and 100% solar PV adoption rates. The 25% scenario could represent the situation in the nearby future and the 100% scenario situation where solar PV installation would be required for all households.

1) 100% PV penetration: Fig. 6 illustrates how network losses develop if all customers on a MV feeder install different size of solar PV systems.

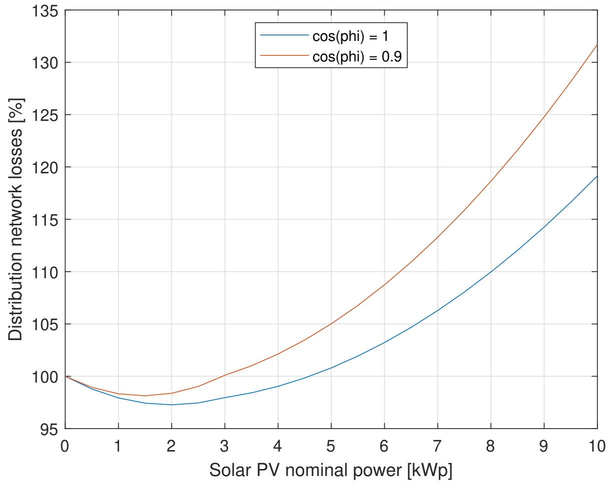

Figure 6. Network losses with PV if all customers install PV systems. 100% equals network losses without PV systems. Reactive power control with constant cosϕ = 1 or 0.9_{ind}.

It can be seen from the figure that distribution network losses decline if all customers have smaller than 4.5 kWp solar PV systems. The losses are at the lowest level when customers have 2 kWp solar PV systems. If solar PV inverters have reactive power control set as cos$\phi = 0.9_{\text{ind}}$ losses are lower with PVs when installations are under 3 kWp. Reactive power control increases the losses but decreases the voltage rise.

2) 25% PV penetration: Fig. 7 illustrates how the network losses develop with different PV sizes if 25% of the customers install PV system on their rooftop without reactive power control. The solar PV systems were allocated to the customers randomly for each simulation. For each solar PV size the customers who will install solar PV systems were randomized only once, which causes variation in the results, but the patterns are clear overall. More precise estimates can be achieved by randomizing the locations of solar PVs customers larger number of times. In this study this was not done because locations of solar PVs do not have that significant effect on the distribution network losses if the PVs are to some extend distributed in different parts of the network [13].

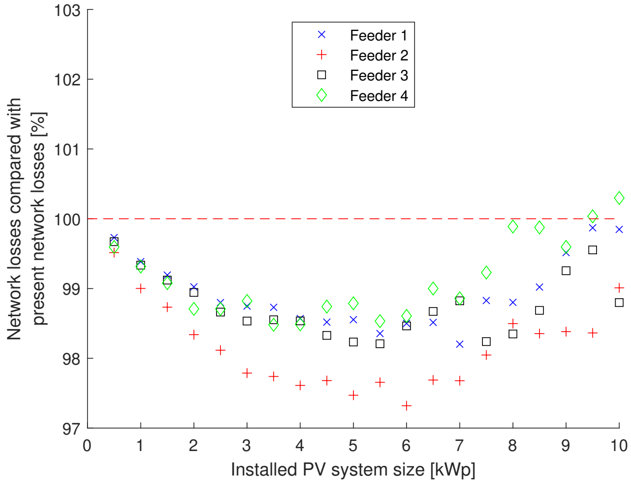

Figure 7. Network losses with PV if 25% of customers install PV systems. 100% equals network losses without PV systems. No reactive power control with solar PV inverters.

It can be seen from the figure that the network losses decrease by 1–2% when installed solar PV systems are approximately 5 kWp. With reasonable dimensioning of household customers' solar PV installations the network losses most likely decrease from the present level.

Fig. 8 illustrates the development of estimated network losses with different solar PV installation capacities when solar PV inverters are set to consume reactive power during production of active power.

It can be seen from the figure that distribution network losses would be lower than present losses, if installed solar PV systems are less than 7 kWp. The curves of different MV feeders are similar, especially when solar PV unit sizes are small.

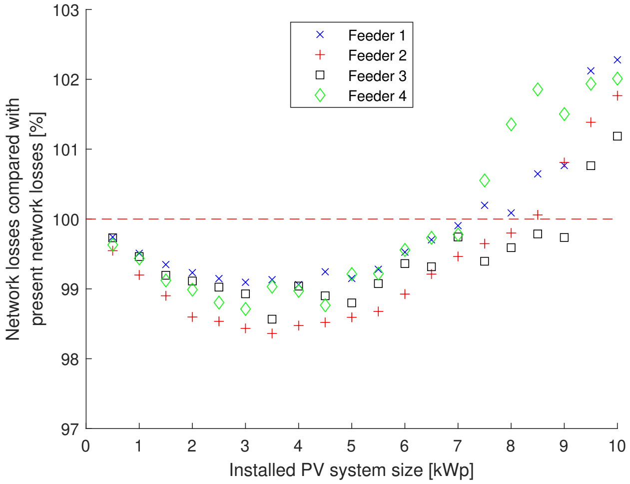

Figure 8. Network losses with PV if 25% of customers install PV systems. 100% equals network losses without PV systems. Constant cosϕ=0.9 reactive power control with solar PV inverters.

C. Costs of network losses

Costs of network losses were estimated by combining estimated hourly network losses and hourly electricity market spot-price data. On electricity price data of year 2020 the 25% penetration of 9 kWp solar PV systems would have decreased the costs of losses by 1.45% compared with the situation without distributed solar PV systems if there was no reactive power control in use. Respectively, if reactive power control was in use, the costs of losses would have increased by 0.4%. If the losses cause approximately 5–6% of the total costs of a DSO and the PV systems and reactive power control can have only a 2% impact on that 5–6%, the cost effect is very minor. However, avoiding unnecessary losses is always important.

V. DISCUSSION

The results show that the network losses can increase during the best solar PV production hours. Currently, these hours have had relatively high electricity market spot prices, but as the number of installed PV production capacity gets larger the higher proportion of midday consumption is covered with low cost production. Thereby, the cost of the network losses may be lower.

The reactive power control of solar PV inverters slightly increases the network losses with high penetration levels. In this study the reactive power control was assumed to be carried out with a constant cosϕ setting, but in reality the losses can be optimized by setting suitable $Q(U)$ control instead of constant cosϕ. The reactive power control with high penetration of PV systems can also affect the reactive power compensation of the distribution networks because solar PV production varies during the day and the DSOs have to pay for exceeding reactive power window set by TSO.

VI. CONCLUSION

The results show that solar PV electricity production can either decrease or increase the network losses depending on installed PV capacities and PV system adoption rates. To minimize the network losses, if all customers would have a PV system, the optimal PV system size would be approximately 2–3 kWp. If the PV systems are installed for 25% of the customers without reactive power control the optimal size to minimize distribution network losses would be approximately 5 kWp. Network losses are on the current level if 10 kWp PV systems are installed for 25% of the customers. Respectively, if constant cosϕ = 0.9 reactive power control is set, the losses are minimized with approximately 4 kWp systems and the losses are equal with the present situation when customers have approximately 7 kWp systems. However, the changes in the distribution network losses are minor.

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