Study of low-voltage distribution grid connection dimensioning principles considering distributed generation in Finland

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STUDY OF LOW-VOLTAGE DISTRIBUTION GRID CONNECTION DIMENSIONING PRINCIPLES CONSIDERING DISTRIBUTED GENERATION IN FINLAND

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ABSTRACT

Solar photovoltaics are becoming increasingly popular on household customers. The distribution networks have been planned for unidirectional power delivery. The solar photovoltaics can cause voltage problems if network capacity is not sufficient. In Finland, the basis of network dimensioning principles considering solar PV systems has been based on equation that estimates the level of rapid voltage fluctuations caused by solar PV system with short-circuit power of the customer connection. This paper presents results of research project "Distribution grid dimensioning principles considering wide-spread distributed solar photovoltaics generation" focusing on the effects of single high-capacity PV systems compared with network capacity. This paper presents a study of update needs of present grid dimensioning recommendation. We evaluate the theoretical background of the parameterization choices in the recommendation. The main finding of this paper is that there are potential update needs in the parameterization of the recommendation.

INTRODUCTION

Energy transition is reshaping the electricity production, and the distributed production units are becoming increasingly popular. The most typical form of distributed generation is solar photovoltaics (PV). In the planning principles of traditional distribution grids, customers have been considered as consumption or production customers, not as prosumers.

In Finland, PV systems have been rare, but the number of new installations has been growing with an accelerating pace during the past five years. The present grid dimensioning principles considering microgeneration have been set approximately 20 years ago. The present methodology is based on calculation of the magnitude of rapid voltage fluctuations, which are limited by the standard SFS-EN 50160. The standard says that the rapid voltage fluctuations generally should not exceed 5% of nominal voltage in low-voltage grids in normal operating conditions but changes up to 10% can occur rarely [1]. The grid dimensioning recommendations set by Finnish Energy, the branch organization for the industrial and labor market policy of the energy sector, are based on the equation,

$$\Delta U = i_{ratio} * S_n / S_{sc} * U_n \quad (1)$$

where i_{ratio} is the ratio of maximum current and nominal current, S_n is the nominal power, S_{sc} is the short circuit power and U_n is the nominal phase-to-ground voltage [2]. The equation has been previously used to define if rotating machines cause voltage quality problems in distribution networks. Concerns have risen within distribution system operators (DSOs) that the use of the equation with the present parametrization may cause improper dimensioning of the distribution grids. The aim of the paper is to analyse the present distribution grid dimensioning considering adoptions of customers' solar PV systems. We analysed from 1 s resolution PV production data how significant the production fluctuations are and how often the PV system's production reaches their nominal power, which can affect the value of the i_{ratio} parameter.

BACKGROUND OF THE STUDY

Solar PV installations in Finland

Solar PV installations have become more and more popular on a global scale during the 2010s. In Finland the spread of solar PVs has been lagging compared to the global pace, but lately the number of installations has been increasing at an accelerating pace [3]. Due to the increasing trend of new installations, but still currently a relatively low number of installations connected to the grid, there is a clear need for proactively analyse if the dimensioning principles correspond to the present knowledge.

Electricity distribution in Finland

Hosting capacity of distribution networks can be significantly dependent on operating conditions. In Finland the two major features affecting the dimensioning of distribution networks are seasonal variation of electric loads and low population density.

Seasonal loads

In Finland, the wintertime heating loads have been a major factor affecting the distribution grid dimensioning. During the lowest outdoor temperatures, the load demand in the distribution grids can be multiple times higher compared with the summer load demands. On the other hand, low load demand during times when the highest solar PV production occurs can cause challenges. Figure 1 illustrates the seasonal nature of a typical electric heated detached house in Finland.

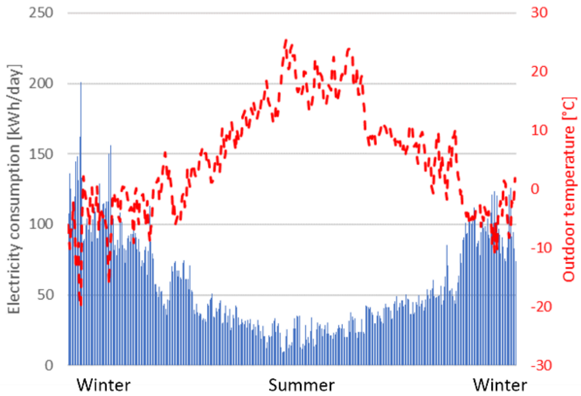

Figure 1 Daily electricity consumption of an electric heated detached house.

Customer density

Finland is a sparsely but almost entirely populated country. Long distances in the rural area networks may cause voltage stiffness problems at the low-voltage connections. On the other hand, this means that capacity strengthening investments can be expensive.

Distribution grid voltage quality

In the electricity distribution networks, voltage quality is an important factor. Electricity production units may cause flicker problems due to rapid voltage fluctuations, or the voltages in the distribution network may rise too high due to power injected to the distribution grid.

Rapid voltage fluctuations & flicker

Rapid voltage fluctuations can cause problems for customer devices or cause disturbing flicker of lights. Rapid changes in network loading can cause voltage fluctuations. This can be problem especially in rural conditions where long distances cause high network impedance.

Voltage level rise

When production exceeds consumption in any part of the distribution network, instead of the voltage dropping the voltage levels begin to rise. Too high voltage levels can damage customers' electric devices, and thus DSO must ensure that the voltage level does not rise above the limits set by standard SFS-EN 50160. Voltage levels can be affected by reactive power control of customers' solar PV inverters. In Finland, the present recommendation sets the inverter parameter for reactive power control to cosφ = 1. In other words, reactive power control is currently not recommended, due to lacking knowledge of suitable settings for Finnish conditions [2].

Electrical safety

In Finland, the DSOs must ensure a minimum short-circuit current of 250 A for connections with a main fuse size of 3x25 A when new connections are installed, or existing networks are renovated [4]. A type C miniature circuit breaker requires 10 times the nominal current for rapid operation. The 250 A limitation in short-circuit current is set higher than 160 A to allow reasonable lengths for protected branch circuits. Currently DSOs have been using the short-circuit power based on 250 A short-circuit current in the equation. An updated version of the standard was published at the end of 2022. In the previous version only 250 A limit for 3x25 A customer connections was provided, but the updated version says that for higher capacity connections the minimum short-circuit current should be correspondingly 10 times higher than the nominal current of the connection [4].

Present dimensioning

The present parametrization and assumptions with the equation would limit the connected PV system size to 6.9 kVA for customers with 3x25 A main fuses. By solving S_n from equation (1),

$$S_{sc} \geq i_{ratio} * \frac{U}{\Delta U} * S_n \tag{2}$$

When the i_{ratio} is assumed to equal 1.0, S_n can be estimated with equation,

$$S_n = \frac{\sqrt{3} * U * i_{sc}}{\frac{U}{\Delta U}} \tag{3}$$

For a 3x25 A connection the maximum connected PV system would be,

$$S_{n(3x25A)} = \frac{\sqrt{3} * 400V * 250A}{\frac{400V}{4\% * 400V}} = 6.9\ kVA$$

This raises the question if the parameterization of the equation is reasonable. The nominal power of a 3x25 A connection is approximately 17 kW, and thus the 6.9 kVA limitation is relatively low.

ANALYSES

Parametrization of the equation was studied to understand how it could be developed to take into consideration the present knowledge of solar PV production characteristics. Therefore, we analysed one second resolution solar PV data, appropriate short-circuit current, safety margins, and the effects of reactive power control.

Production data analysis

To understand which kinds of rapid voltage fluctuations solar PVs can cause, production data from LUT University's solar PV units was analysed. LUT University has registered production powers of several production units on one second resolution during multiple years [5]. The data from three production units was analysed. These production units were,

a) Carport, solar panels on a parking lot cover 108 kW_p panels direction to south with slope of 15°.
b) Flat-roof system, solar panels on a rooftop of LUT University, 51.5 kW_p of PV panels, installed facing south with slope angle of 15°.
c) Solar Tracker, PV system that turns panels to follow the Sun. 5.1 kW_p.

Figure 2 demonstrates the solar PV production during different summer days.

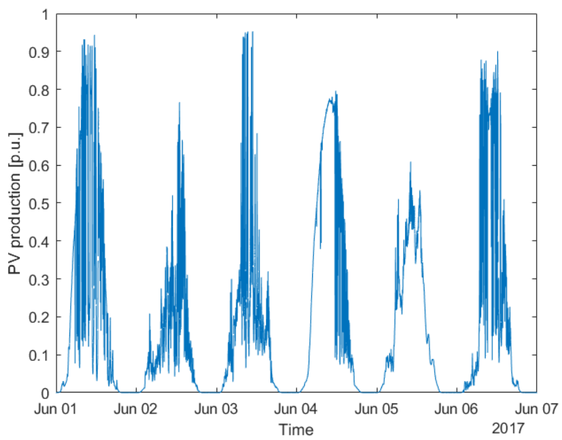

Figure 2 Solar PV production during summer days.

It can be seen from the figure that the produced power can vary depending on the weather. The 4th of June shows the profile during a mostly sunny day. The effects of clouds shading the PV system can be clearly seen during other days. During a sunny day the peak production power is approximately 70%–80% of the nominal power of the PV system. Reflected solar radiation can increase the produced power momentarily at the level of nominal power. Figure 3 illustrates the solar PV production on 1 s resolution during 4.5 months.

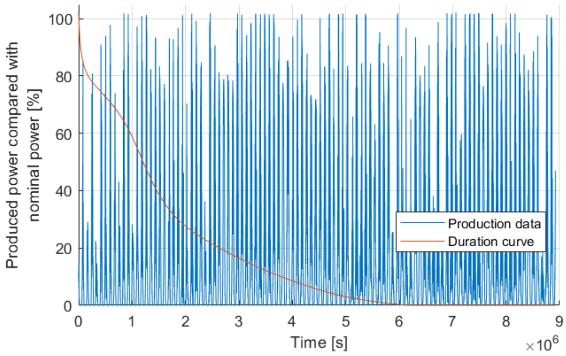

Figure 3 Solar PV production on 1 s resolution during summer.

It can be seen from the figure that in Finnish conditions the solar PV production rarely equals the nominal power of the system. Moments when the production approaches the nominal power occur through the summer. Figure 4 illustrates the variation of output power of the solar PV system in 1 s resolution.

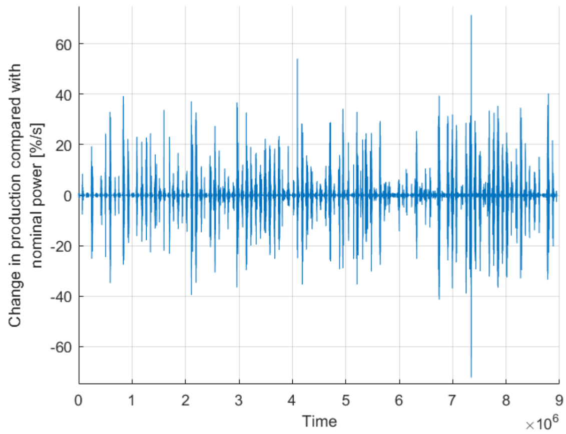

Figure 4 Changes in the PV production output power compared with nominal power of the solar PV system.

It can be seen from the figure that rapid variations in solar PV production are low compared with the nominal power of the system. The highest 1 s variations in the studied three solar PV systems were approximately 70% of the nominal power of the systems. Even though due to the scale of the x-axis it seems in Figure 4 that there are rapid changes in the production, the changes are in fact relatively slow and would not cause voltage fluctuation problems. Thereby, the value of the i_{ratio} parameter could be lower than the present 1.0.

Short-circuit current analysis

The present dimensioning recommendation is based on two principles, the equal treatment of customers and the 250 A minimum short-circuit current that DSOs ensure. Due to the earthing conditions in Finland, DSO's low-voltage grids' earthing are typically TN-C and customers' installations are TN-S. The short-circuit impedances in different faults can differ, and thus, it is important to use appropriate values of short-circuit current in the equation.

In unsymmetrical faults the short-circuit impedance must be evaluated considering the sequence networks and the values of PE and PEN conductors. The minimum short-circuit current is always lower than the three-phase short-circuit current. For example, the two-phase line-to-line short-circuit current is approximately 87% of the three-phase one. When the low-voltage network is long, and thus the short-circuit currents are low, the single phase-to-ground short-circuit current is lower than the three-phase short-circuit current. The ratio depends mostly on the distribution transformer and the impedance of low-voltage PE and PEN conductors.

Present solar PV installations that are connected to the distribution networks are mostly three-phase production units. Thereby, the 250 A parameterization of the short-circuit current in the equation gives an overly pessimistic estimate for the voltage quality consequences of connected solar PV systems.

ΔU/U ratio

In the recommendation the ratio of ΔU/U has been set to 4% [2]. However, the standard SFS-EN 50160 says that rapid voltage fluctuations should not generally exceed 5% in normal conditions, but up to 10% changes can occur rarely. Thus, the 4% recommendation already sets a safety margin in the dimensioning.

Reactive power control

With reactive power control the customer connection point voltages can be increased or decreased without affecting the active power production. In the equation reactive power control has not been considered. The effects of reactive power control are dependent on the X/R ratio of the supplying distribution network. Figure 5 illustrates the effect of reactive power control on voltage change if the X/R ratio is 0.5 with different short-circuit currents and a 10 kW_p solar PV system.

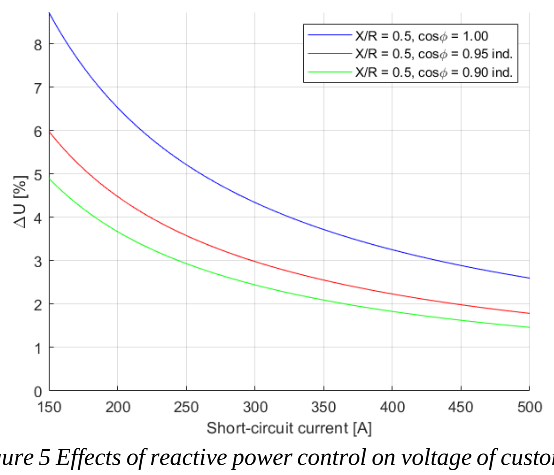

Figure 5 Effects of reactive power control on voltage of customer connections with different short-circuit currents.

It can be seen from the figure that reactive power control can have significant effect on the voltage rise. The simulation was made with X/R ratio of 0.5 that represents a typical low-voltage network. This depends mainly on size of the distribution transformer and low-voltage network line length supplying the connection. This also supports the idea of decreasing the value of i_{ratio}.

RESULTS

Our studies indicate that the parameterizations in the recommendation could be updated to consider the present knowledge of solar PV system characteristics. The equation currently in use provides a simple way to estimate the effects of a single solar PV system to the distribution network voltage rise and potential voltage fluctuations, especially if reactive power control is not utilized.

Parameterization of the equation

The parametrization of the equation includes multiple choices that cause safety margins in the grid dimensioning. It is reasonable to consider at least the three-phase short-circuit current instead of single-phase short-circuit current, which is typically the lowest short-circuit current when voltage stability is low.

Table 1 shows the limitations for connected PV systems considering different recommendation scenarios. In the present scenario 250 A short-circuit current limitation is the same for all customers with lower than 3x63 A main fuses. In scenario A, the short-circuit current is at least 10 times higher than the nominal current of customer connection also on customers with larger than 3x25 A connection. In scenario B, the 15% difference in three-phase and single-phase short-circuit currents is considered in addition to scenario A. Scenario C considers in addition lower value of i_{ratio}, 0.80.

Table 1 Limitations of connected solar PV systems with different considered dimensioning scenarios.

	Scenario				Connection
	Present	A	B	C	capacity
Main fuse size	kVA	kVA	kVA	kVA	kVA
3x25 A	6.9	6.9	7.9	9.9	17.3
3x35 A	6.9	9.7	11.1	13.9	24.2
3x50 A	6.9	13.8	15.9	19.8	34.5
3x63 A	8.8	17.4	20.0	25.4	43.5
3x80 A	11.7	22.1	25.0	31.7	55.2

It can be seen from the table that the update in the standard SFS 6000-8-801, which sets higher short-circuit current requirement for connections larger than 3x25A, has a high impact on the PV size limits. It also has to be considered that the equation does not take into account the combined effect of multiple solar PV systems on voltage rise. The voltage rise caused by multiple PVs was excluded from the scope of this paper, but it was studied in the project report [6].

DISCUSSION

Efficient use of hosting capacity

Short-circuit currents typically affect the low-voltage grid planning only in rural conditions, where customers can be located up to 1 000 m away from the feeding distribution transformer. In urban areas the short-circuit currents in customer connection points are significantly higher than the required 250 A. Thus, strict following of the recommendation may lead to unnecessarily restrictive dimensioning rules of the connected production units in some conditions. Equal treatment of the customers is an important principle when considering a monopoly business operating critical infrastructure. On the other hand, restriction of connected production unit size may waste potential of connected renewable energy in locations where the grid is already stiff. The energy transition will require significant efforts, and thus unnecessary limitations should be avoided. Restriction of solar PV systems may also cause unwanted publicity for the DSO and harm the company image.

Meaning of reasonable dimensioning principles

There are two potential undesired outcomes if the dimensioning principles are not reasonable. First, a DSO can set too strict limitations to connected PV, which may delay the energy transition or cause unnecessary premature investments to the distribution networks. Secondly, if the connected solar PV system power has no limitations or the limitations are too loose, the network capacity may be exceeded. Especially when there are many solar PV units in same low-voltage networks the voltage rising problems may require grid strengthening investments.

Voltage fluctuation limit

The recommendation sets more strict limitation to the voltage fluctuations than the standardization. The voltage quality standard limits the rapid voltage variations in normal conditions to 5%, whereas the present recommendation for grid dimensioning has a safety margin, which allows only 4%. Based on the results of our study it seems that rapid significant changes in solar PV output power are rare. The standard allows rarely occurring up to 10% voltage fluctuations, and thus it should be considered if the fast variations in the solar PV production are so rare that this could be considered in the dimensioning principles.

Voltage rise with high penetration of PVs

It must be considered that the equation does not consider effects of multiple solar PV units. When the PV penetration is higher the voltage level will rise. The challenges caused by voltage rise can be estimated by simulating solar PV systems on network model and performing power flow calculations.

CONCLUSIONS

The target of this study was to evaluate the present dimensioning principles of distribution networks considering customer-side solar PV systems. We studied the theoretical background of the parametrization choices of short-circuit power, and how the reactive power control can affect the results. The equation provided in the recommendation gives a simple way to estimate if a solar PV system causes problems in a certain distribution network location, but it does not consider the combined effect of multiple solar PV systems. Our results show that there are several assumptions that cause overlapping margins of safety in the dimensioning, and thus the parametrization of the equation could be reconsidered. On the other hand, the approach of the equation does not consider if there are multiple systems connected to close locations, and thus voltage-level rising problems might occur.

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