Energy Proceedings
Vol 61, 2025
ISSN 2004-2965

Overvoltage Analysis in Norwegian Distribution Test Bench Grid with High PV Penetration[#]

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ABSTRACT

This article presents a literature review on the most relevant quality parameters for hosting capacity in the Nordic context. A distribution grid from Norway is presented in detail to be established as a test bench for further studies. The grid covers different voltage levels, from 47 to 0.4 kV.

A hosting capacity analysis is performed on the proposed grid. The solar PV hosting capacity of the proposed grid has been estimated for a PV penetration of about 160% when voltage limits are considered. It was determined that the transformer and cable ratings are the main concerns in determining the hosting capacity, rather than the voltage deviations. This is in line with the findings of the literature review. We argue that this is the case for most grids in the Nordic.

Keywords: Distribution system, Distributed generation, Hosting capacity, Photovoltaic systems, Power systems.

NONMENCLATURE

Abbreviations	
ADMD	After Diversity Maximum Demand
DSO	Distribution System Operator
Ei	Swedish Energy Markets Inspectorate
IEEE	Institute of Electrical and Electronics Engineers
PCC	Point of Common Coupling
TSO	Transmission System Operator

1. INTRODUCTION

There are several standard grids available that are used as test benches to study hosting capacity in power systems. Different topologies, like the ones from IEEE or CIRED, analyse different challenges at different voltage levels. The use of standard grids is very useful, as researchers can compare their results. The Norwegian grid presented in [1] is of great interest in this context. The grid is analysed in this article and the parameters required to simulate the grid are presented, so that it can be established as a test bench.

The specific features of distribution grids in the Nordic countries requires a dedicated test bench. The population density is lower than in other European countries. Feeders at the 0.4 kV level are usually not longer than 300 m, but there are exceptions. Lines of almost two km in length are found in some Northern areas [2]. The scarce use of gas for domestic heating and cooking reflects on the usage of electricity with higher peak power and After Diversity Maximum Demand (ADMD) than their Southern neighbours.

Distribution grids in Sweden are divided into Rural and Regional grids. Even with the wide spread of distribution companies (there are about 160 distribution companies), we find some general patterns. Voltage regulators in the form of tap changers are usually installed in the transformers between the 40-50 kV to 11 kV level (although tap changers in secondary substations between 11/0.4 kV level can be found) [2]. In general, 11 kV grid have a stable voltage through the year. It should be considered for dynamic analysis of the grid that Petersen coils are common in the medium voltage substations.

The hosting capacity is defined as the level of new loads or generation that may be added to the grid before the quality indicators deteriorate upon unacceptable [3]. The indicators include harmonic content, unbalances between phases, flickering, losses and so on, but the most studied limits are the voltage magnitude and line/transformer loading. The Swedish Energy Markets Inspectorate (Ei) is the Governmental body that

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[#] This is a paper for the Resilient-Applied Energy Symposium and Forum: Resilient energy systems (Resilient2025), Sep. 23-25, 2025, Västerås, Sweden.

regulates the electricity network operations in Sweden and establishes the quality parameters for the grid. The voltage deviation limits are evaluated at the connection point of the client. The voltage drop is shared between the Regional and Rural grids. The Regional grid is usually simplified as its Thevenin's equivalent and only the low voltage grid is simulated in hosting capacity studies. The voltage drop that the author assigns to each operator influences the hosting capacity.

There are 3 main methods to calculate the hosting capacity: deterministic, stochastic and time series [3]. Deterministic analysis is done with a snapshot of a worst-case scenario. The power rating of a feeder is determined by the addition of all the individual loads, reduced by a simultaneity factor (such as Velander's formula). Some authors refer to this value as the ADMD. The rating of the transformer is found in the same way, with the addition of the individual loads. The rating of the transformer is lower than the sum of the feeders because they have different simultaneity factor. The rating of the transformer may be as low as 70% of the ADMD [4].

2. HOSTING CAPACITY LIMITS FOR VOLTAGES AND LOADING

2.1 Voltage limit

Most grid codes establish the voltage variation between ±10% of the nominal magnitude [5], [6]. The distribution grid is fed from a medium voltage grid with fluctuating voltage. Voltage regulators in the form of tap changer transformers are common on the 47 kV level [2]. Voltage regulators at the secondary substations (0.4 kV) are usually not automatic and consists of a summer and winter setting. Setting a constant voltage at the 47 kV substation and not at the 0.4 kV level is therefore a reasonable assumption. A common practice is to simulate the secondary substation at nominal voltage and allow a voltage fluctuation of ±5% at the client's PCC. The other ±5% of allowed voltage fluctuation is left for the upstream grid. Each grid operators have their reference values; E.On designs the 11 kV network so that the voltage drop shall not exceed 4% [4], and Vattenfall aims to keep the voltage fluctuations in the 0.4 kV grid under 4% [7]. Loop impedances in feeders are also limited, reducing the voltage drop even further.

The voltage limit is set by Ei in Sweden that is based on the EN 50160 Standard. The voltage band is ±10% for 95% of the time during a week. The standard is fulfilled with a measurement over a week, taking the mean value every 10 minutes. Short trips away from the voltage limits are allowed by the norm.

2.2 Overcurrent

The nominal rating for lines and transformers is determined by the thermal dissipation of the components. There is usually a different current limit for lines in summer and winter due to the difference in the estimated ambient temperature. Considering that the physical limit is thermal, most grid codes allow overcurrents for short periods of time. The nominal power limits of components are local to each grid operator. For example, the TSO in Denmark allows overloads of 130% in transformers, while Finland allows 150% for brief periods [8]. The hosting capacity will be different when nominal or allowed ratings are considered. It is therefore difficult to compare hosting capacity limits based on violations of current and voltage limits.

3. THE NORWEGIAN MEDIUM AND LOW VOLTAGE POWER DISTRIBUTION SYSTEM

The grid model used in the present study was taken from [1]. It is based on a real distribution grid located in Norway. The grid parameters were supplied by the Norwegian DSO Norgesnett and were anonymised and simplified prior to publication. The model includes the line parameters for most of the 11 kV lines, but not for the lower voltage lines and no transformer impedances were provided in the dataset. The data set is completed in the following sections.

The original model is divided in two sections that are disconnected in normal operation. Each section has a 47 kV node that feeds the 11 kV grid from only one substation. The 11 kV grids are connected, but this link is open in normal operation. It is common to find lines in medium voltage grids that are only closed during maintenance or under disturbances. The reason for those open lines is to operate medium voltage with a radial structure but keeping an alternative feeding path. Simulating the transmission and upstream grid is not giving relevant information for hosting capacity analysis as the voltage in the 47 kV grid is fairly stable. Transformers feeding the 47 kV grid are usually equipped with voltage regulators in the form or tap changers [2]. Both parts of the grid are completely independent during normal operation, so we decided to choose only one of them for our study. The grid topology used in this study is presented in Figure 1.

The 0.4 kV grids lack line parameters in the studied model. We assigned an impedance and nominal power to all lines. The low voltage grid in this test case corresponds to industrial loads. Another alternative to study a residential area is to substitute the grid behind the 11/0.4 kV transformer with the complete grid as the ones presented in [9].

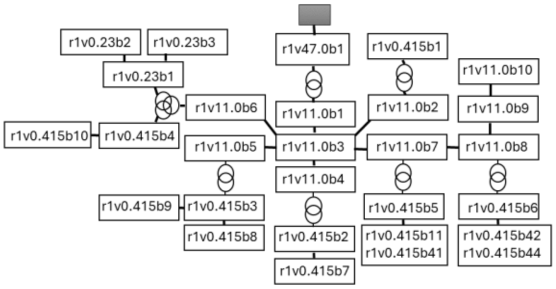

Fig. 1 Schematic of the Norwegian Medium and Low Voltage grid used in this study

3.1 Line and transformer parameter estimation

The low voltage cables were selected based on the thermal rating in the standard SS 424 14 24 [10]. An excerpt from the standard can be seen in Table 1. In this study it is assumed that only a selection of cable types (those listed in the table) are used, which is common practice. Each cable serving one customer was selected such that the thermal limit was not exceeded during the studied time span.

The transformer parameters are estimated based on the peak power supplied to the feeder downstream. There are standard transformer ratings, so the transformer rating is chosen the closest over to the peak power. The parameters are chosen accordingly.

The values used in this study for the line and transformer parameters are presented in the Appendix.

Conductor area (mm2)	Thermal limit, current (A)
25	57
50	84
95	129
150	170

Table 1 Thermal limit of PVC-insulated

3.2 Power transformer ratings

The transformer ratings are not given in the original model [1]. An estimation of the power ratings of the transformers is done using the peak power of the time series of the load. The transformer nameplate ratings are higher than the maximum power that goes through them, and has a standard size for use on residential developments [4]. Table 2 shows the estimated ratings of the transformers.

From bus	To bus	Power (kVA)
r1v11.0b4	r1v0.415b2	1,000
r1v11.0b7	r1v0.415b5	500
r1v11.0b8	r1v0.415b6	315
r1v11.0b2	r1v0.415b1	200
r1v11.0b5	r1v0.415b3	200
r1v11.0b6	r1v0.415b4	200
r1v11.0b6	r1v0.23b1	315

Table 2 Nameplate ratings of the transformers in the grid

3.3 0.4 kV grid

The 0.4 kV grid presented in [1] is missing the line impedance parameters. The peak power through the lines is used to estimate the peak current. The impedances are calculated with the values from Table 1 and an estimation of the distance between substations. The estimated values required to simulate the grid are presented in the Appendix.

3.4 Load and irradiation data

Load buses in the reference grid have an associated load profile. They consist of hourly data from the 1st of March 2019 to the 1st of March 2020. PV production is simulated using the irradiation and temperature data from a weather station in Skjetlein located near Trondheim, Norway [11].

4. METHODS

The model is implemented in the open-source function package MATPOWER [12] that runs in Matlab. The grid is simulated with the resolution of the available input data, that is in steps of 1 hour. The time span ranges from 1st of March 2019 to 1st of March 2020.

The grid is fed by a 47 kV node that is simulated as an infinite bus with constant voltage 1 p.u. This assumption is due to the common use of voltage regulators in transformation stations in this voltage level.

The model is tested without PV production to obtain a base case to compare. The scenario with high penetration of PV production is created by including PV generation at each load bus in the grid. A minimum nominal power in the PV modules is introduced such that nodes with less than 11 kW of consumption are simulated with a nominal 11 kW power of PV production. No generation is included in the 7 buses without any demand. The production included at each time step in the simulation is the nominal power multiplied by the irradiation factor (from 1 to 0) obtained from [11].

5. RESULTS

5.1 Base model

In Figure 2, the voltage variations at each node are shown across the simulation time series, for the case with no PV installed. The voltage never exceeds 1 p.u., while the lowest voltage is found at the 0.4 kV level at 0.92 p.u.

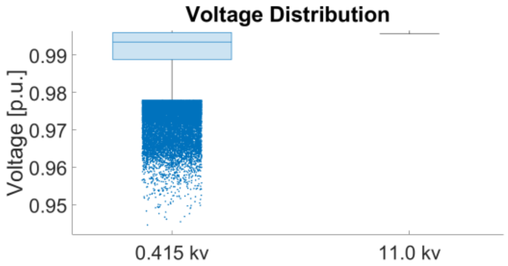

Fig. 2 Overview of the voltage fluctuations during the year for different voltage levels

As expected, the variations in voltage over at the 11 kV grid are very low. Measurements in real grids show also that the 11 kV grid is very stable, with variations in the order of only 0.1 % [13].

5.2 Hosting capacity

The power production has been increased in small steps until overvoltage of 1.1 p.u. appeared. This represents a PV penetration level of 160% when considering voltage fluctuations, where the nominal PV power at each node matches its historical peak demand over the time series. The resulting total PV power installed in the grid is 4.01 MW. Figure 3 displays the voltage levels at each load bus. Only one load bus, r1v023b2, experiences a peak voltage slightly above 1.1 p.u., exceeding this threshold for just 2 hours during the entire simulation period. The overlapping of the total production and consumption is presented in Figure 4.

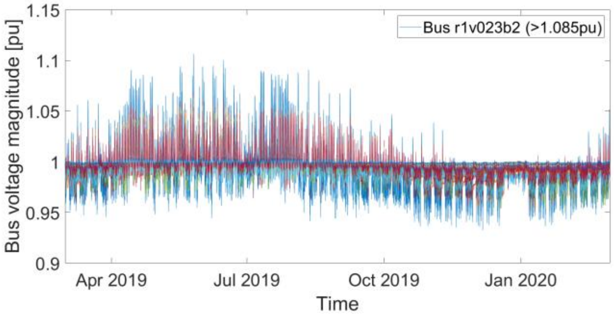

Fig. 3 Voltage levels at each load bus over the simulation period. The load bus highlighted in the legend is the only one that exceeds 1.1 p.u.

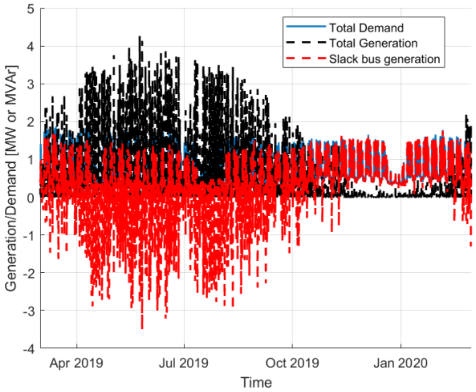

Fig. 4 Total power and consumption in the grid for the simulation period

5.2.1 Overvoltages

There is only one node in the grid with voltages over 1.1 p.u. (r1v023b2), as presented in figure 3. Ei sets voltage limit at 10% of the nominal voltage. Compliance is achieved if the voltage remains within this limit for at least 95% of the time over a one-week period. Therefore, brief over voltages do not constitute a code violation, that is, over 8.4 hours during a week. The voltages exceeding 10% are observed for only 2 hours of the year (on 26 May 2019), so it does not formally constitute a violation of the grid code. The study continues finding the voltage limit that is surpassed over 9 hours in a week, that is 1.085 p.u. in this case.

The voltage in node r1v023b2 is over 1.085 p.u. for 41 non-consecutive hours during a year. The distribution of the voltage events over 1.085 p.u. per week is presented in Figure 5. Based on this data, we could conclude that the voltage remains under 1.085 p.u. during 95% of the time during a week.

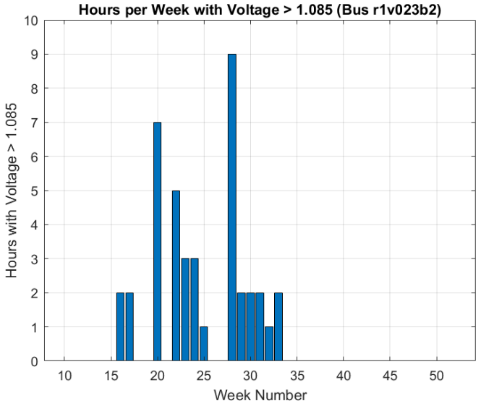

Fig. 5 Hours of voltage level greater than 1.085 p.u. per week, for node r1v023b2

5.2.2 Overcurrents

Figure 6 shows the power through the transformers during the times series analysed. There are 6 transformers that reach 100% of nominal capacity, and two of them that surpasses the 150% limit (the transformer between nodes r1v11.0b7 and r1v0.415b5 marked in red and between nodes r1v11.0b5 and r1v0.415b3, marked in blue in the figure).

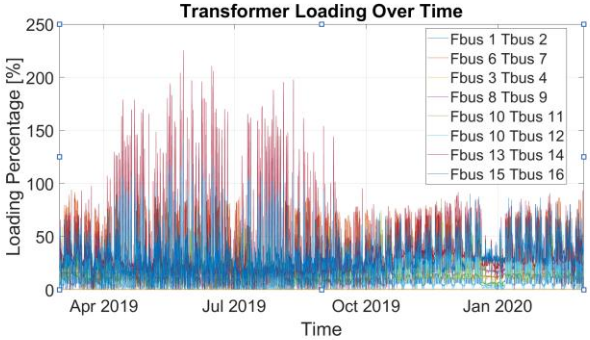

Fig. 6 The plot shows the voltage profile at load bus r1v023b2 over the simulation period. The voltage exceeds 1.1 p.u. only during 2 hours on 26 May 2019

6. CONCLUSIONS

The main performance indices in hosting capacity analyses are the voltage deviations and the current limits. The study of overvoltages dominates academic articles because the control of voltage regulation devices is an interesting technology to increase the hosting capacity. The literature review presented showed that the current ratings in transformer are more restrictive than voltage fluctuations in real grids.

The parameters of a distribution grid from Norway have been presented in this article. Authors argue that this grid is a relevant test bench to study distribution grids in the context of the Nordic countries.

Time-series simulations from the base case show similar behaviour as real grids presented in literature. The 11 kV grid has little voltage fluctuation [13]. The hosting capacity analysis based on voltage fluctuations shows that the grid can host more PV production than there is demand. The peak power at the slack bus is due to production and not from demand, suggesting that the power rating for the lines and transformers are more restrictive than the voltage fluctuations. This is the expected behaviour for the Nordic countries.

The authors will continue developing this grid and tuning some parameters to establish it as a standard for grid studies in the Nordic countries. These insights can guide DSOs and planners in designing more resilient, PV-friendly networks in the Nordic context.

ACKNOWLEDGEMENT

This work was supported by the Competence Centre for RESILIENT Energy Systems. This work was conducted within the STandUP for Energy strategic research framework.

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APENDIX: LINE PARAMETERS OF THE GRID

mpc.baseMVA = 10;

F_BUS	T_BUS	BR_R	BR_X
r1v47.0b1	r1v11.0b1	0,01000	0,05000
r1v11.0b1	r1v11.0b3	0,00768	0,00640
r1v11.0b3	r1v11.0b4	0,00380	0,00340
r1v11.0b4	r1v0.415b2	0,10000	0,50000
r1v0.415b2	r1v0.415b7	0,08384	0,00000
r1v11.0b3	r1v11.0b2	0,00878	0,00329
r1v11.0b2	r1v0.415b1	1,00000	5,00000
r1v11.0b3	r1v11.0b5	0,00380	0,00340
r1v11.0b5	r1v0.415b3	1,00000	5,00000
r1v0.415b3	r1v0.415b8	0,37209	0,00000
r1v0.415b3	r1v0.415b9	0,89442	0,00000
r1v11.0b3	r1v11.0b6	0,00213	0,00178
r1v11.0b6	r1v0.415b4	1,00000	5,00000
r1v0.415b4	r1v0.415b10	0,91163	0,00000
r1v11.0b6	r1v0.23b1	0,31700	1,58500
r1v0.23b1	r1v0.23b2	2,97674	0,00000
r1v0.23b1	r1v0.23b3	3,16279	0,00000
r1v11.0b3	r1v11.0b7	0,00341	0,00491
r1v11.0b7	r1v0.415b5	0,20000	1,00000
r1v11.0b7	r1v11.0b8	0,00472	0,00680
r1v11.0b8	r1v0.415b6	0,31700	1,58500
r1v0.415b5	r1v0.415b11	4,88372	0,00000
r1v0.415b5	r1v0.415b12	5,23256	0,00000
r1v0.415b5	r1v0.415b13	2,06047	0,00000
r1v0.415b5	r1v0.415b14	5,93023	0,00000
r1v0.415b5	r1v0.415b15	6,27907	0,00000
r1v0.415b5	r1v0.415b16	2,44680	0,00000
r1v0.415b5	r1v0.415b17	6,97674	0,00000
r1v0.415b5	r1v0.415b18	7,32558	0,00000
r1v0.415b5	r1v0.415b19	2,83314	0,00000
r1v0.415b5	r1v0.415b20	8,02326	0,00000
r1v0.415b5	r1v0.415b21	8,37209	0,00000
r1v0.415b5	r1v0.415b22	0,74855	0,00000
r1v0.415b5	r1v0.415b23	2,41860	0,00000
r1v0.415b5	r1v0.415b24	9,41860	0,00000
r1v0.415b5	r1v0.415b25	9,76744	0,00000
r1v0.415b5	r1v0.415b26	10,11628	0,00000
r1v0.415b5	r1v0.415b27	10,46512	0,00000
r1v0.415b5	r1v0.415b28	10,81395	0,00000
r1v0.415b5	r1v0.415b29	11,16279	0,00000
r1v0.415b5	r1v0.415b30	11,51163	0,00000
r1v0.415b5	r1v0.415b31	11,86047	0,00000
r1v0.415b5	r1v0.415b32	12,20930	0,00000
r1v0.415b5	r1v0.415b33	12,55814	0,00000
r1v0.415b5	r1v0.415b34	12,90698	0,00000
r1v0.415b5	r1v0.415b35	13,25581	0,00000
r1v0.415b5	r1v0.415b36	13,60465	0,00000
r1v0.415b5	r1v0.415b37	13,95349	0,00000
r1v0.415b5	r1v0.415b38	14,30233	0,00000
r1v0.415b5	r1v0.415b39	14,65116	0,00000
r1v0.415b5	r1v0.415b40	15,00000	0,00000
r1v0.415b5	r1v0.415b41	15,34884	0,00000
r1v0.415b6	r1v0.415b42	2,09302	0,00000
r1v0.415b6	r1v0.415b43	2,75465	0,00000
r1v0.415b6	r1v0.415b44	4,37209	0,00000
r1v11.0b8	r1v11.0b9	0,00022	0,00031
r1v11.0b9	r1v11.0b10	0,00258	0,00372
r2v11.0b1	r2v11.0b2	0,00306	0,00393
r2v11.0b2	r2v11.0b3	0,00380	0,00340
r2v11.0b2	r2v11.0b5	0,00380	0,00340
r2v11.0b2	r2v11.0b7	0,00572	0,00458
r2v11.0b7	r2v11.0b8	0,00029	0,00023
r2v11.0b8	r2v11.0b9	0,00418	0,00078
r1v11.0b10	r2v11.0b2	0,00269	0,00387
r2v47.0b1	r2v11.0b1	0,01000	0,05000
r2v11.0b3	r2v11.0b4	0,00380	0,00340
r2v11.0b5	r2v11.0b6	0,00380	0,00340
r2v11.0b7	r2v0.415b1	0,01000	0,05000
r2v11.0b8	r2v0.415b7	0,01000	0,05000
r2v11.0b9	r2v0.415b2	0,01000	0,05000
r2v11.0b4	r2v0.415b3	0,01000	0,05000
r2v11.0b6	r2v0.415b4	0,01000	0,05000
r2v0.415b1	r2v0.415b5	0,23953	0,00000
r2v0.415b1	r2v0.415b6	0,51163	0,00000
r2v0.415b2	r2v0.415b8	0,08384	0,00000