Impacts of extremely high and low electricity prices on low-voltage networks in rural areas of Finland

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IMPACTS OF EXTREMELY HIGH AND LOW ELECTRICITY PRICES ON LOW-VOLTAGE NETWORKS IN RURAL AREAS OF FINLAND

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Abstract

Two exceptional events happened during the winter 2023-2024. In November 2023 the electricity spot-priced dropped to -500 €/MWh in Finnish bidding area. In January 2024 the electricity spot-price rose almost up to 1900 €/MWh. These extreme price events caused incentive for spot-price-based electricity contract customers to react. Impacts of this price-driven electricity usage to low voltage (LV) networks of rural area in Finland is studied by using real hourly AMR meter data acquired from Finnish electricity retail operator.

1. Introduction

The transition to renewable energy has caused price fluctuations in Finnish electricity prices, primarily due to wind power. By the end of 2024, Finland had over 8 GW of installed wind power capacity, producing roughly 18% of its electricity [1]. With 1.4 GW of new capacity under construction as of 14.1.2025 wind power growth is expected to continue [2]. Industrial-scale solar power projects are also progressing and may play a larger role in the future. Generally, higher wind power production leads to lower spot prices and vice versa. Additionally, crises in Europe, such as the war in Ukraine, have further increased price fluctuations.

The type of electricity contract affects the flexibility of the customer's consumption. Fixed-price electricity contracts, traditionally the most popular in Finland, have seen price increases due to market uncertainties. Currently, about one-third of contracts are spot-price-based contracts [3]. In a spot-price-based electricity contract, the price of electricity is determined for each hour by the day-ahead (DA) market of the power exchange Nord Pool. These types of contracts encourage customers to adjust consumption based on market prices.

1.1. Objective of the study

Objective of the study is to show how market driven electricity consumption effects to voltage and transformer load power in LV network during extreme price events. The research question in the paper is:

- How market driven electricity consumption effects to customer point voltage and transformer load power in Finnish rural are LV networks?

2. Background of the study

Between 2023 and 2024, two notable events occurred in the Finnish electricity price: on November 24th, the market price dropped to -500 €/MWh due to a faulty offer, and on January 5th, it spiked to 1900 €/MWh due to a prolonged cold period, unexpected shutdowns of large power plants, and low wind power production.

2.1. A week of very low prices

Fault offer on the DA market in Finnish bidding area caused record low spot prices. A retail company offered on average roughly 5.5 GW of electricity which did not exist in very low price [4]. That amount corresponded to about half of Finland's need on that day [4]. Finnish transmission system operator (TSO) Fingrid had to encourage electricity producers to not react on negative price by scaling down the production. There were also fear of consumer side reaction to the negative price. Even though there weren't any excess electricity production the price signal might suggest to use more electricity. Especially to the customer who had spot-price-based electricity contracts at that time. TSO informed customers to not use electricity abnormally [4]. In this paper this week is referred as Black Friday week.

2.2. A week of very high prices

A prolonged cold period led to record high electricity prices on 5th of January. Temperatures of -30°C persisted for a week, increasing heating demands. Outages at large power plants and moderate wind power production further pressured price. The TSO and government urged citizens to save electricity, successfully reducing usage by over 1000 MW when spot price was at its highest [5]. This paper refers to this period as Blue Friday week. Both Black Friday and Blue Friday weeks represent rare extreme price events, with Blue Friday-like occurrences being more likely. The Finnish TSO, has predicted capacity adequacy risks for winter 2024-2025, highlighting the potential impact of prolonged cold, windless periods, and power plant outages [6].

3. Data and Methodology

Target of this study is to simulate the effect of implicit DR to LV grid. Simulation is done with OpenDSS software which is designed for power flow calculations. Consumption data is hourly smart meter data of real customers, and it is obtained from Finnish electricity retail company.

3.1. Nord Pool spot prices data

Price data consists of hourly DA spot price data from Nord Pool. Because this paper concentrates on Finnish electric system the prices are Finnish bidding area prices.

3.2. Hourly AMR consumption data

Customer data is gathered from a dataset of Finnish electricity retail company. Dataset consists of hourly consumption data of more than 6000 customers from years 2019-2024. Customers are located in different parts of Finland. Dataset includes customer contract type information and location of the customer based on the nearest weather station. Customer contract types are divided into three groups which are non-fixed-term contract, fixed-term contract and spot-price-based contract. In this paper contracts are divided into to two groups which are fixed-price contracts and spot-price-based contracts. Analysis period of this paper is 1.1.2023 - 15.3.2024. The number of customers who have spot-price-based contracts or fixed price contracts during the analysis period is 2823.

3.3. Simulation topologies and customer groups

Network consists of transformer circuit and the effects of medium voltage (MV) network is not taken to account. The simulation network parameters are based on three different Finnish DSO distribution networks in a rural area. Topologies of the simulation transformer circuits are generic, but they represent typical topologies in rural areas in Finland. There are seven customers in both topologies. Figures 1 and 2 show the topologies used in simulations.

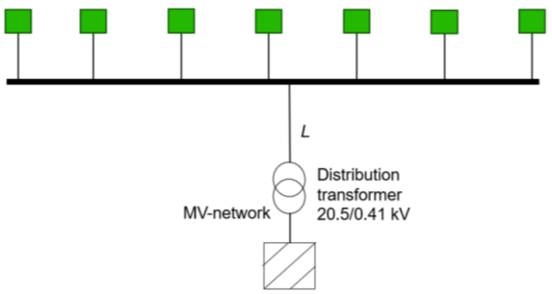

Fig. 1. Topology A.

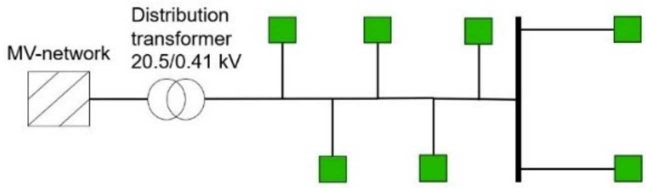

Fig. 2. Topology B.

To study the effect of market driven DR two customer groups are formed: flexible and non-flexible customer group. Both groups have same criteria regarding peak power, annual electricity consumption, customers are chosen from the same municipality area and customers must have same contract type during the analysis period. Peak power criterion is under 25 kWh/h because it filters in customers that have 3x25A main fuse which is typical in detached house in Finland. Annual electricity consumption criterion is over 7 MWh which cut outs apartment blocks from the groups. Same geographical location helps at comparing results when temperature conditions are same. In addition to above non-flexible customer group have a criterion of fixed-price electricity contract. Customers flexibility is determined by negative correlation coefficient with spot price and consumption. Thereby, criterion for the flexible customer is negative correlation coefficient in Black Friday week and Blue Friday week and spot-price-based contract during the analysis period. Figure 3 shows the flexible (upper) and non-flexible (lower) customer groups peak powers and annual electricity consumption in relation to all customers which had contracts in analysis period.

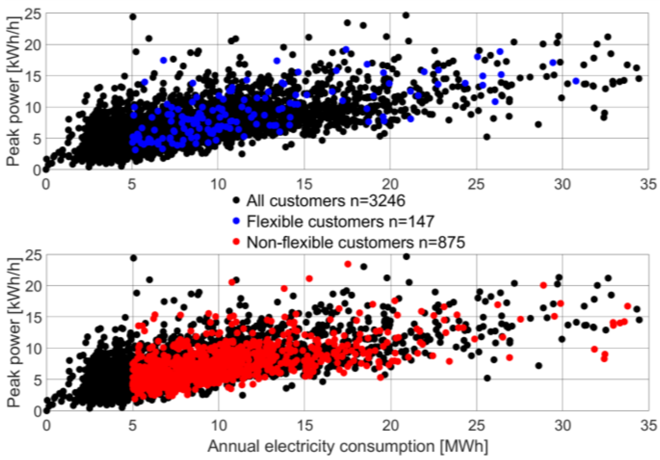

Fig. 3. Annual electricity consumption and peak power of every customer of the dataset from 2023.

Figure 3 shows that there are more customers in non-flexible group than in flexible customer group. In both customer groups the density of customers is largest in 7 - 15 MWh annual electricity consumption region.

4. Results

Results are divided into to two sections: results of a week of very low prices and a week of very high prices.

4.1. A week of very low prices

Figure 4 shows the Pearson's correlation coefficient in Black Friday week for both customer groups in simulation and for all customers which had fixed price contract or spot-price-based contract during the whole analysis period.

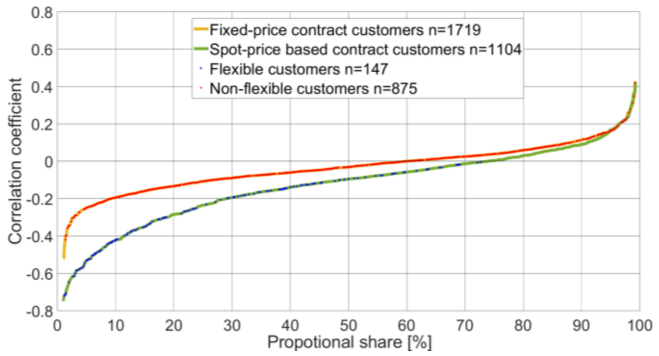

Fig. 4. Spot price and consumption correlation coefficient in Black Friday week.

During Black Friday week, the larger proportion of customers had a negative correlation coefficient than positive. Blue dots show all the flexible customer and red dots non-flexible customer. Because of the flexible customer criterion all the blue dots settle on the negative correlation side of the spot price contract curve. Non-flexible customers settle across the fixed price contract curve. The difference between the curves of spot price customers and fixed price customers is noticeable.

Figure 5 shows the average power of both groups of customers as a function of the spot price in the Black Friday week.

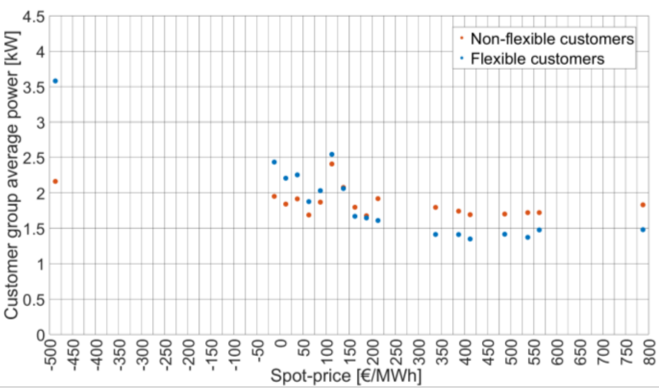

Fig. 5. Average power of both customer groups according to spot-prices in Black Friday week.

In figure 5 spot prices are divided into different price ranges from -500 €/MWh to 800 €/MWh with step size 25. Figure 5 shows that in price ranges under 100 €/MWh the average power of flexible customer group is higher than in non-flexible customer group. The most significant difference between the average powers is at the lowest price range -500 – 475 €/MWh when flexible customer groups average power is over 1 kW higher than non-flexible groups average power. Figure 6 shows customer point voltage in topology A during Black Friday week of two different customer groups.

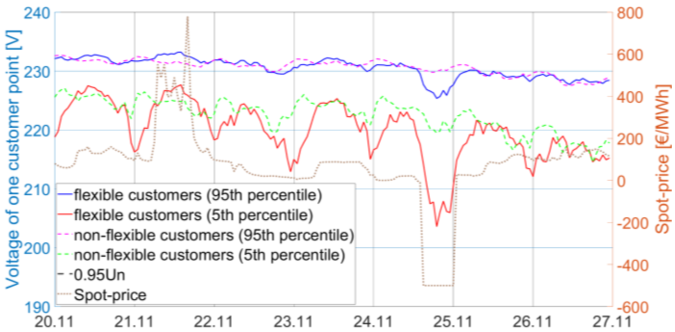

Fig. 6. Topology A customer point voltage during Black Friday week.

Figure 6 Solid blue and red lines show the 95th and 5th percentiles voltages of the simulations of the flexible customer group. Dashed purple and green lines show the 95th and 5th percentiles of the simulation's voltages of the non-flexible customer group. Figure 6 shows that the lowest voltage value comes at the same time as the minimum price during the Black Friday week. The use of flexible customer groups of electricity is cyclical and daily voltage dip is timed to midnight. At 95th percentage point simulation the voltage during the minimum price is almost 10 V lower than the second lowest dip in flexible customer group simulation. Voltage drops under 210 V during the negative prices. In non-flexible customer group simulation, there is no evident reaction to spot price changes in voltage. Figure 7 shows the transformer load power during the Black Friday week.

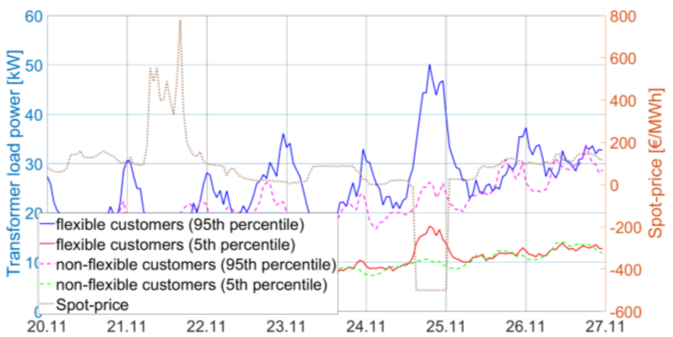

Fig.7. Topology A transformer load power during Black Friday week.

Peak transformer load power caused by flexible customer group is significant during the negative price.

Figure 8 shows the voltage of farthest customer point in topology B during Black Friday week.

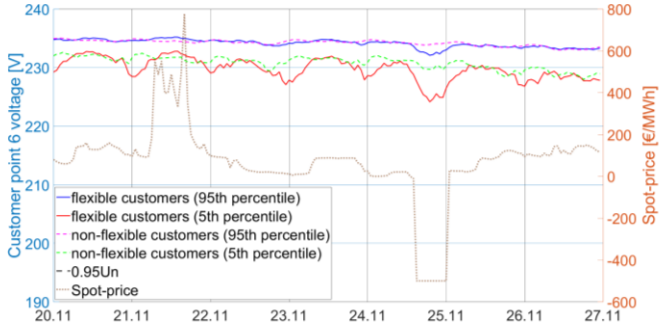

Fig. 8. Topology B customer point 6 voltage during Black Friday week.

Simulation results of topology B shows that the effect to the customer point voltage caused by reaction to negative price is more moderate compared to results of topology A. Voltage does not drop under 220 V in farthest customer point of topology B.

4.2. A week of very high prices

Figure 9 shows the correlation coefficient of all customers that had spot price-based contract and fixed price contract during the analysis period in Blue Friday week.

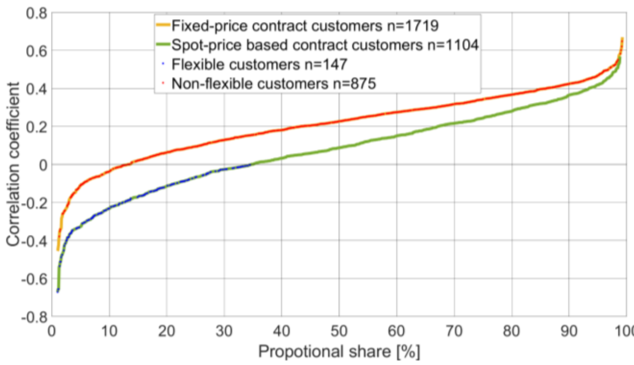

Fig. 9. Correlation coefficient of spot price and consumption during Blue Friday week.

When figures 4 and 9 are compared, it is found that a higher proportions of customers in a Black Friday week have a negative correlation coefficient than in a Blue Friday week. One of the reasons for this is that the Blue Friday was cold week and that might lower the willingness to adjust the consumption down during expensive price hours. This is especially the case for customers who have electric heating. Figure 10 shows average power of flexible and non-flexible customer groups in function of spot price during Blue Friday week.

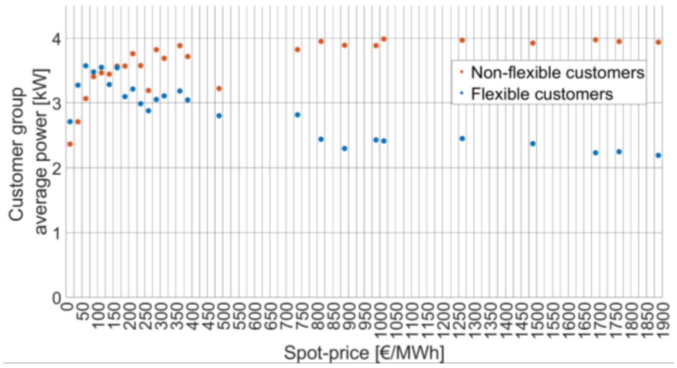

Fig. 10. Average power of both customer groups according to the spot price in Blue Friday week

Figure 10 shows that during extremely high prices average power of non-flexible customer group is bigger than flexible customer groups average power. However, prices from 0 €/MWh to 100 €/MWh flexible customer groups average power is bigger. Figure 10 is logical because non-flexible customer group don't have incentive to lower consumption during high prices. Figure 10 implicates that non-flexible customer group may include customers which have electric heating. This can explain why non-flexible customer groups average power is bigger during high prices.

Figure 11 show voltage in flexible and non-flexible customer group simulations in topology A during Blue Friday week.

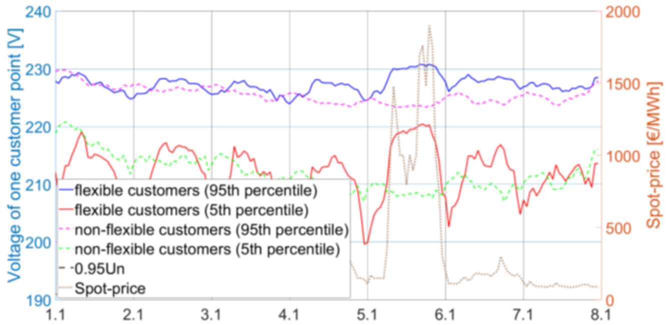

Fig. 11. Customer point voltage during Blue Friday week in topology A.

In figure 11 at worst, voltage drops almost under 200 V in flexible group simulation. The non-flexible customer group does not seem to react to spot price changes. Noteworthy is that when comparing the voltages of flexible customer group during Black Friday and Blue Friday week the daily voltage dip in Blue Friday week is lower than the voltage dip during the negative price in Black Friday week.

Figure 12 show topology A transformer load power during Blue Friday week.

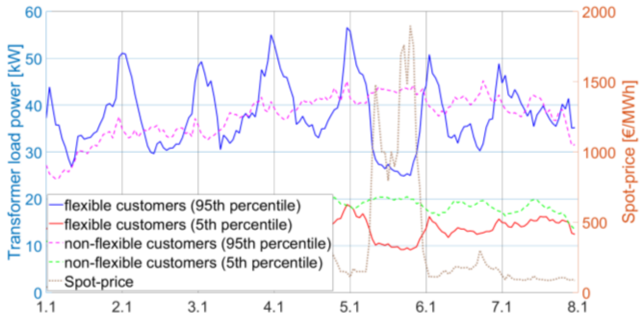

Fig. 12. Transformer load power during Blue Friday week in topology A.

Figure 12 shows that flexible customer groups cyclical electricity consumption is more evident in Blue Friday than in Black Friday week. Daily peak load power tends to time during midnight. This might implicate that there are customers which have electric storage heating in flexible group. There might also be EV charging, that is timed to midnight. This is caused by the lower spot prices during nighttime. In flexible customer group simulation reaction to price can be seen during the high prices (5.1.2024). Load power peaks occur right before and after the high prices. In 95th percentage point simulation load power is over 20 kW lower during high prices than right before high prices. Figure 13 shows voltage of the farthest customer point in topology B during the Blue Friday week.

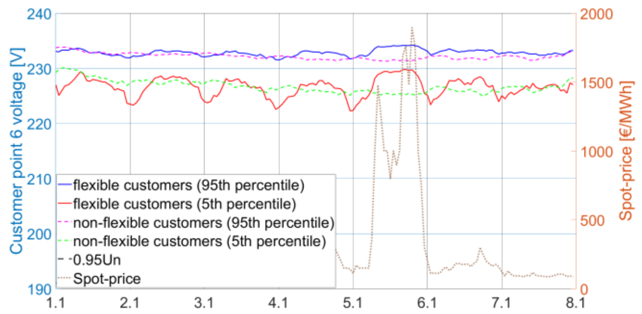

Fig. 13. Customer point 6 voltage in topology B during Blue Friday week.

Voltage fluctuation is more moderate in topology B than in topology A. Voltage does not fall under 95 percent of the nominal voltage at any moment in either simulation.

5. Discussion

Results shows that there is synchronization effect in flexible customer group. However, it only caused the need for network reinforcement in topology A. Topology was more significant than customer group in simulations, with lower customer point voltages.

Flexible customers' synchronized electricity consumption causes larger peak loads, typically around midnight, with transformer load power fluctuating over 10 kW during high prices. Non-flexible customers have more stable load power and voltage. Flexibility was assessed by the negative Pearson's correlation coefficient between spot price and consumption during Black Friday and Blue Friday weeks. When considering the relevance of the network analysis of this paper it must be considered that while spot prices during Black Friday and Blue Friday weeks are rare, Blue Friday-like events are more likely to recur. Black Friday's negative prices were due to a market mistake, making recurrence less likely.

6. Conclusion

Target of this study was to simulate how market driven electricity consumption affects LV networks. Simulation was done with OpenDSS software using Monte Carlo method. Effects studied in this paper were transformer load power and customer point voltage. Customer groups used in simulations were formed from dataset which consists real hourly customer AMR data. Customers were divided into two groups flexible and non-flexible groups. Flexibility was determined with two criteria spot-price-based contract, and negative correlation of spot price and electricity consumption during extremely high and low-price weeks. Simulation results depict worst case scenario because the extremely high and low-price events are rare. According to the simulation results market driven electricity consumption may cause voltage fluctuation if topology is challenging.

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