RISK OR BENEFIT ON THE ELECTRICITY GRID: DISTRIBUTED ENERGY STORAGES IN SYSTEM SERVICES

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ABSTRACT

This paper considers the effects of distributed energy storages on electricity distribution systems in the situation where the storages are used in system services such as frequency containment. In the paper the energy storage scenario is based on the assumption where the present energy-based electricity distribution pricing model will be changed to power-based, which motivates electricity customers to reduce their peak loads, and thus to invest in energy storages.

INTRODUCTION

The paper focuses on the assessing of the risks of undesired management of distributed electric energy storages on electricity distribution grids. Distributed resources provide a new opportunity to be used as a resource for system level services such as frequency containment. However, the synchronized operation of distributed storages as the system services may cause undesired effects on the distribution grid level. The risk is relevant in the case when the base load of the distribution network is high and it may realize if the surplus production in the system leads to over-frequency in power system. In that case, energy storages switch on charging mode increasing load and possibility of overloading of the distribution networks increases.

Variety of active resources such as distributed battery energy storages (BES) increases in the near future. Thus, the distributed energy resources become a significant part of electrical power system. On the other hand, the electricity distribution and markets are developing in a way that rewards the owners of flexible and controllable loads. For instance, there are discussion [1]–[4] of transition from the prevailing energy-based electricity distribution to power-based distribution pricing giving incentives to invest in BES [5],[6]. In addition, Frequency Containment Reserve (FCR) market in the electricity markets is a place where the capability to respond in system frequency variation is paid providing possible BES owners an opportunity to earn money. Thus, the BES owners are potential group to participate in frequency support [7].

A factor that promotes energy storages is the present price trend. History has shown that unit prices of the storages have fallen fast and the indications from the industry supports continuing of the trend. For instance, a paper [8] shows that battery pack costs have decreased rapidly. If the BES unit prices were 1 000 €/kWh in year 2010 after 2015 the prices are below 500 €/kWh. The price trend is supported by the announcements of Tesla with their energy storage application Powerwall II [9], which retail price is below 400 €/kWh excl. value added tax (VAT).

The analysis in the paper is based on hourly mean loads from the similar time period provided by automatic meter reading (AMR). This is combined with the capacities of BES to participate in system level services such as FCR to analyse the effects of the BES on the electricity distribution grids. This can be analysed, when the load data are joint with the grid topology.

BES APPLICATIONS

The studies have shown that BES applications can be used to several applications providing benefits for their owners including electricity end-users. This may lead to situation where distributed energy storages have become general in electricity distribution systems.

Energy storages can be utilised in several application providing wide scale benefits for several power system actors such as the end-user itself, the controller of power system stability, local distribution system operator and balance responsible party in the electricity retail business. The BES applications can be divided to primary and secondary [10]. Typically the primary applications can be divided to 1st peak cut/peak load reduction of the end-users load demand [5],[6], 2nd photovoltaic electricity production storage and 3rd price arbitrage in the spot markets. Ancillary service markets are typically categorised as secondary application.

The BES can be used to several purposes even simultaneously but the primary application of the BES is set as priority number one. The primary application of the BES determines partially the restrictions for the use of the BES on the other applications. For instance, the load demand levelling with the peak cut application may restrict the output/input power of the BES.

In this study the focus is restricted in the analysis of BES utilization in FCR (ancillary service).

FREQUENCY CONTAINMENT

In the Nordic countries electrical power system frequency is nominally 50 Hz and it is controlled by national transmission system operators. They are obliged to ensure that power system has enough controllable capacity available for system primary control meaning Frequency containment in system normal operation (FCR-N) or in disturbances (FCR-D). In the Nordic level this means 600 MW capacity for FCR-N and 1000 MW for FCR-D, of which Finnish obligation for FCR-N is 140 MW and for FCR-D the obligation is 260 MW.

Determined reserve market products FCR-N and FCR-D participate in frequency containment with synchronised rules. The activation of the reserves are precisely determined. For instance, in Finland the commitments of the FCR are determined by the national transmission system operator Fingrid [11].

For instance, the FCR-N is the first reserve that reacts when the frequency crosses the limits of the normal frequency band, which is between 49.95 Hz and 50.05 Hz. The dead band is illustrated in Figure 1 showing an example of one hour frequency deviation.

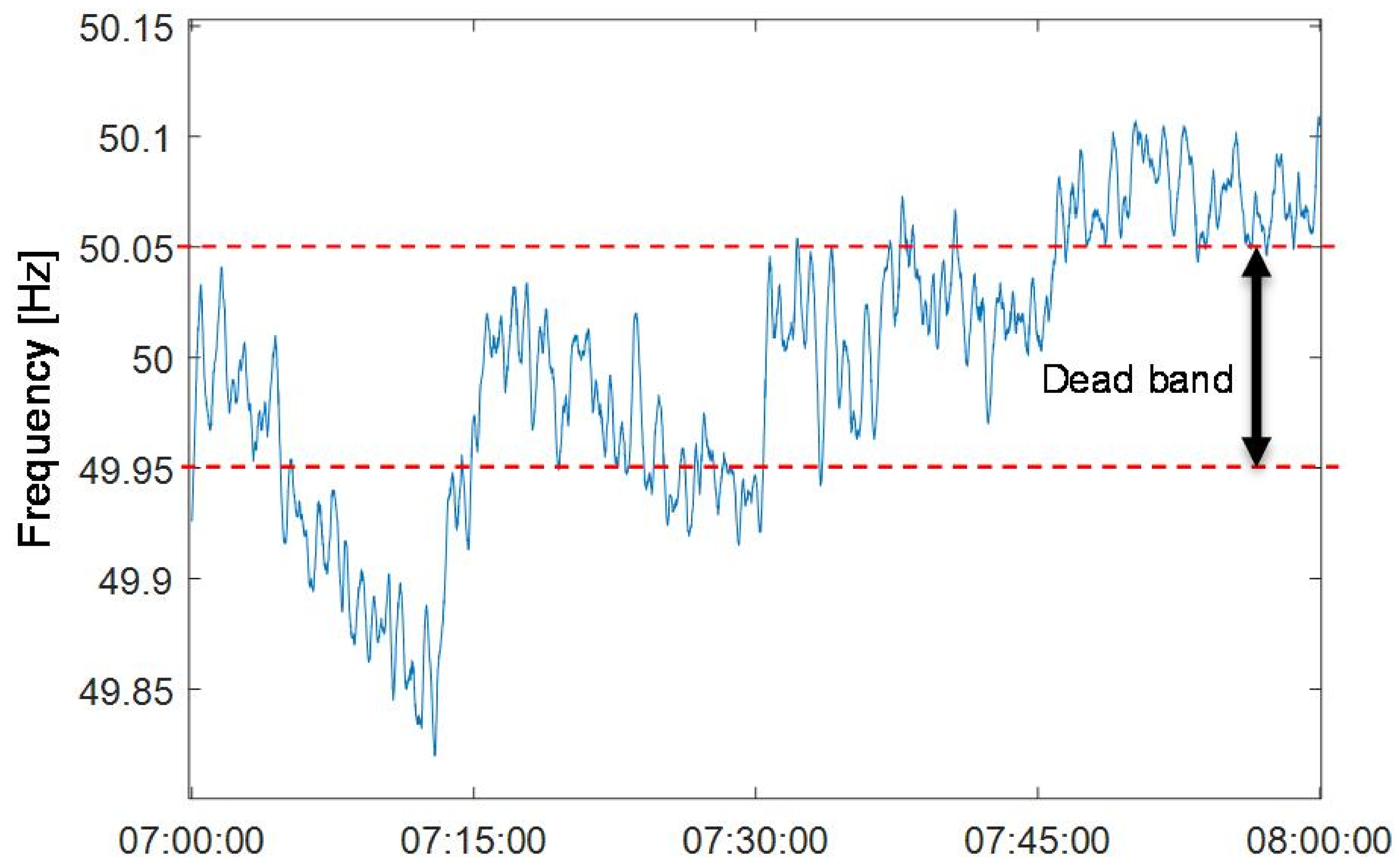

Figure 1. One hour snapshot of frequency in Nordic electrical power system on Sunday 4th February in 2013.

When the frequency falls below 49.95 Hz more electricity production is required meaning power up-regulation or less consumption and when the frequency exceeds 50.05 Hz less electricity production is required meaning power down-regulation or more consumption to meet the production and consumption balance. Furthermore, according to reserve instructions [11] up-regulation of FCR-N reserve has to be adjusted so that reserve reacts when the frequency falls below 49.95 Hz and full up-regulation power is reached when frequency crosses 49.90 Hz. Correspondingly, in case of down-regulation, when the reserve reacts at 50.05 Hz, the full power down-regulation is reached when the frequency exceeds 50.10 Hz. An example of a droop curve of the reserve participating in FCR-N is presented in Figure 2.

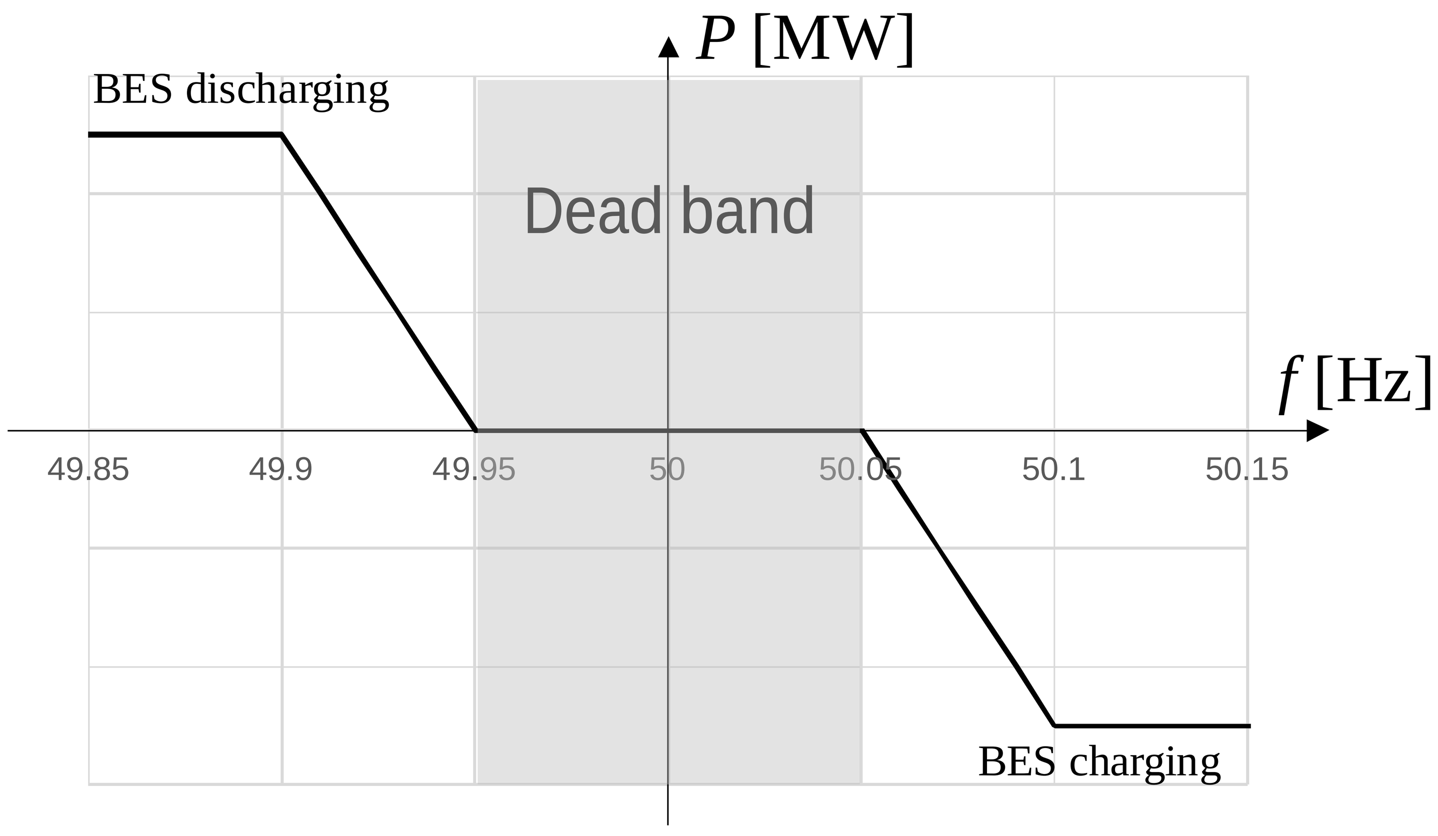

Figure 2. An example droop curve of a reserve participating in FCR-N.

Correspondingly to FCR-N reserve, FCR-D reserve has its own activation rules [11]. As the name of the reserve describes, it is the reserve for disturbances and it reacts only when the power system has serious unbalance between production and consumption. Often this occurs when important power plants drops out of power system. The activation frequency for FCR-D is 49.90 Hz and it has to reach full operation power when frequency is 49.50 Hz.

Battery energy storages in frequency containment

Battery energy storages appears from the system point of view both as power producer and consumer depending. Thus, when BES participates in FCR it can be a power producer when the frequency decreases below the limit value and the frequency exceed the upper limit the BES is shown as a consumer. Traditionally, power flows in the distribution networks downstream from medium-voltage (MV) towards low-voltage (LV) networks, which means that typically the worst case with the energy storages is when all of the storages behave as consumer i.e. they are charged with a synchronous signal due to over-frequency ($f > 50.05$ Hz).

Battery energy storages are potential actors to participate in frequency reserve because they are capable to quickly adjust power output/input. However, even the BES is capable to respond quickly in frequency changes, the capacity of distributed BES is rarely high enough to participate in reserve market auction where the minimum bid size is currently 100 kW for an hour. This means that in the market has to be an operator or operators, which can form a pool of battery energy storages which participates in the reserve markets as a whole.

METHODOLOGY

In this study we focus to consider the effects of BES on electricity distribution networks in the situation where they are used in power system frequency containment. The analysis is approached so that present loading of the network is compared with the situation where the energy storages are implemented and further used as FCR. The implementation of energy storages is based on approach where the present widely used energy-based distribution tariff structure is changed to power-based distribution tariff, where the distribution price depends on the peak power of the customer. This provides electricity customers incentive to invest in BES, which makes electricity customers able to reduce their peak loads, which can be carried out with a BES [5], [6]. This approach means that all the BES capacity is not available all the time because the power consumption can already be at the maximum load demand level which is predetermined based on load statistics analysis. Thus, in the analysis the priority number one is the peak load reduction and the FCR applications are at the second priority level.

The steps of the approach are described as follows:

1. Validation of AMR data sets and electricity distribution network containing MV lines, secondary transformers and LV distribution lines.
2. Power flow with present AMR measured hourly load curves
3. Profitability analysis of BES for the customers based on power-based tariff and new hourly load curves for the customers with reduced peak loads
4. Power flow with modified hourly load curves (peak loads reduced)
5. Analysis of capability of customers to participate in FCR with their BES so that customers peak power will not rise and thus no extra costs are established due to FCR operation
6. New load curves of the customers with the assumed participation in FCR
7. Power flow with modified hourly load curves (peak loads reduced + participation in FCR)
8. Comparison of the load changes between the final (step 7) power flow and the initial power flow (step 2) or power flow with BES (step 4)

CASE STUDY

The risk of BES on electrical system is studied with the case where the BES are involved in FCR. The analyses have been carried out for a network of a Finnish electricity distribution system operator (DSO) (Nivos Oy). The network comprises 10 800 electricity customers consuming annually 173 GWh electrical energy making 16 MWh per customer per year. A majority of the customers are found in the category of detached house customers. The analyses with the data have been carried out in Matlab where a simulation model has been built based on the AMR and network data.

The case area consists of three primary substation areas with 28 MV distribution feeders. The distribution network has 540 km of MV network, 890 km of LV network and 700 secondary distribution transformers. The customer density (network length/a customer) is 132 m per customer in the case area.

Number of distributed energy storages

The earlier studies show that power-based tariffs compose incentives to invest in energy storages. In the study BES price is 500 €/kWh, lifetime of BES is 10 years and power-based distribution fee is 10 €/kW for each month, which provides DSO a revenue that fits with the Finnish regulatory framework.

In this study this approach indicates 8670 distributed energy storages in the case network if all the theoretically feasible storages are implemented if the present energy-based tariff structure is changed to power-based. If the smallest energy storages, less than 3 kWh, are left out of the approach, the number of storages is 3400. In the case where the smallest storages are left out from the consideration, the average size of the storages is 4.0 kWh, of which input/output power is assumed to 4 kW. Thus, the total energy capacity of the distributed BES is 13.5 MWh.

BES in frequency containment

Frequency containment reserves participating in so called normal operation (FCR-N) are committed to adjust their power output/input depending on the frequency. If the frequency exceeds the nominal frequency the load of the network should be increased or production should be decreased meaning that the BES takes power from the network. Respectively, if the frequency drops below the nominal point the loads should be decreased or power production should be increased meaning that the BES supplies power to the network.

The highest proportion of the BES capacity, which can be used to frequency containment is 50% of its energy capacity (assuming that it can supply enough power to fulfil the power criteria) so that it can respond to under- or over-frequency continuously with the full hour if required. The 50% proportion is consequence of the bidirectional feature of FCR-N market. The reserve policy [11] requires that the reserve should be able to participate in power up- and down-regulation. For instance, if the capacity of BES is 10 kWh, the owner can provide 5 kW of its capacity to the aggregator operating in FCR-N market. In addition this means that in principle the state of charge (SOC) of the BES should be near 50% before the operation hour in FCR-N market, meaning 5 kWh charge for 10 kWh BES.

Because the main purpose of the BES is to ensure that hourly electricity consumption does not exceed the predetermined target power, full BES capacity may not be available all the time for the frequency containment. In the study we assume that 100% of the BES owners participate in FCR-N with 25% or 50% capacity of the BES each hour if the BES is not already used in peak load reduction. 25% capacity means 3.4 MW reserve power and 50% capacity is 6.8 MW.

Network effects

The effects of the storages used in system services on the peak loading of the network are presented in the following table and figures. Table 1 presents the average load changes in the analysed scenarios compared with the initial loading of the distribution network divided in the following component groups: LV lines, secondary transformers and MV lines. Equal classification is used in Figure 3 – Figure 5, which illustrate load changes in each line kilometre or transformer.

Table 1. Average load changes in distribution network compared with the initial loading of the component

	Peak load reduction	Peak load reduction + 25% FCR-N	Peak load reduction + 50% FCR-N
LV lines	-10.0%	-8.9%	-8.0%
Transformers	-4.0%	-0.6%	+2.1%
MV lines	-1.6%	+2.5%	+6.0%

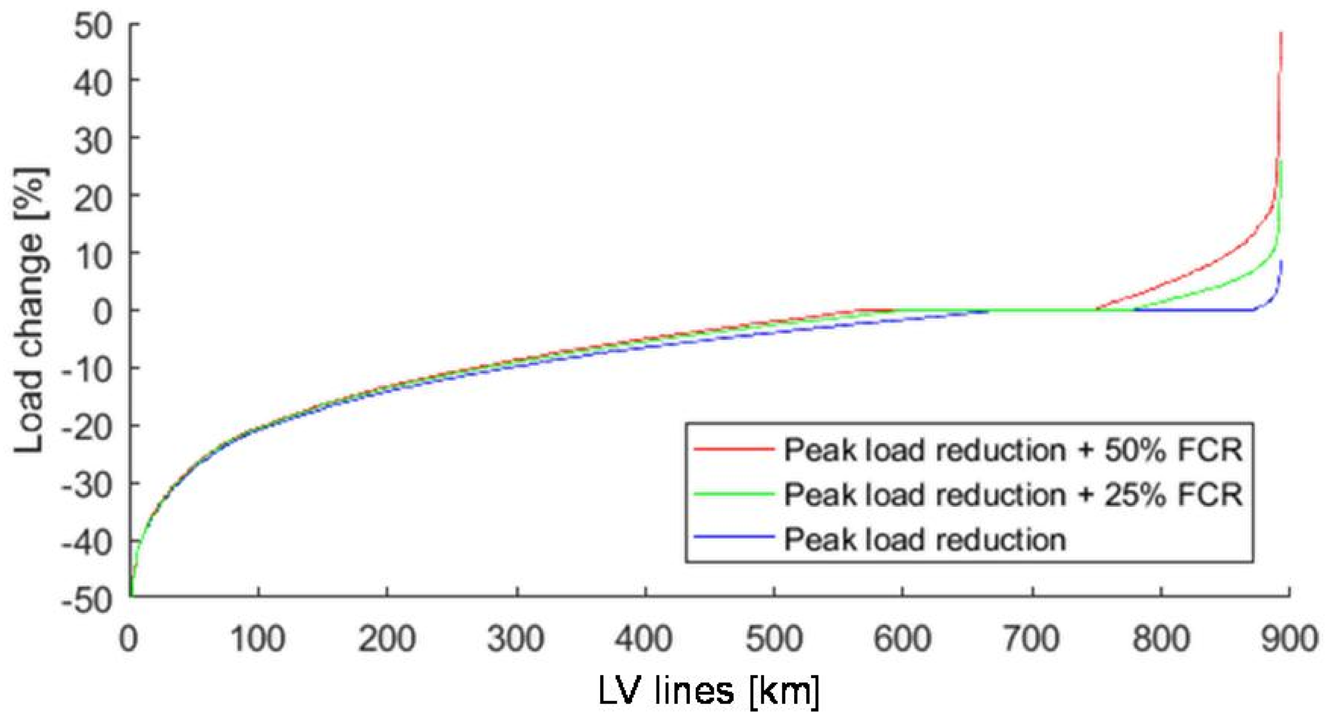

Figure 3. Load changes of LV lines compared with the initial load of the lines.

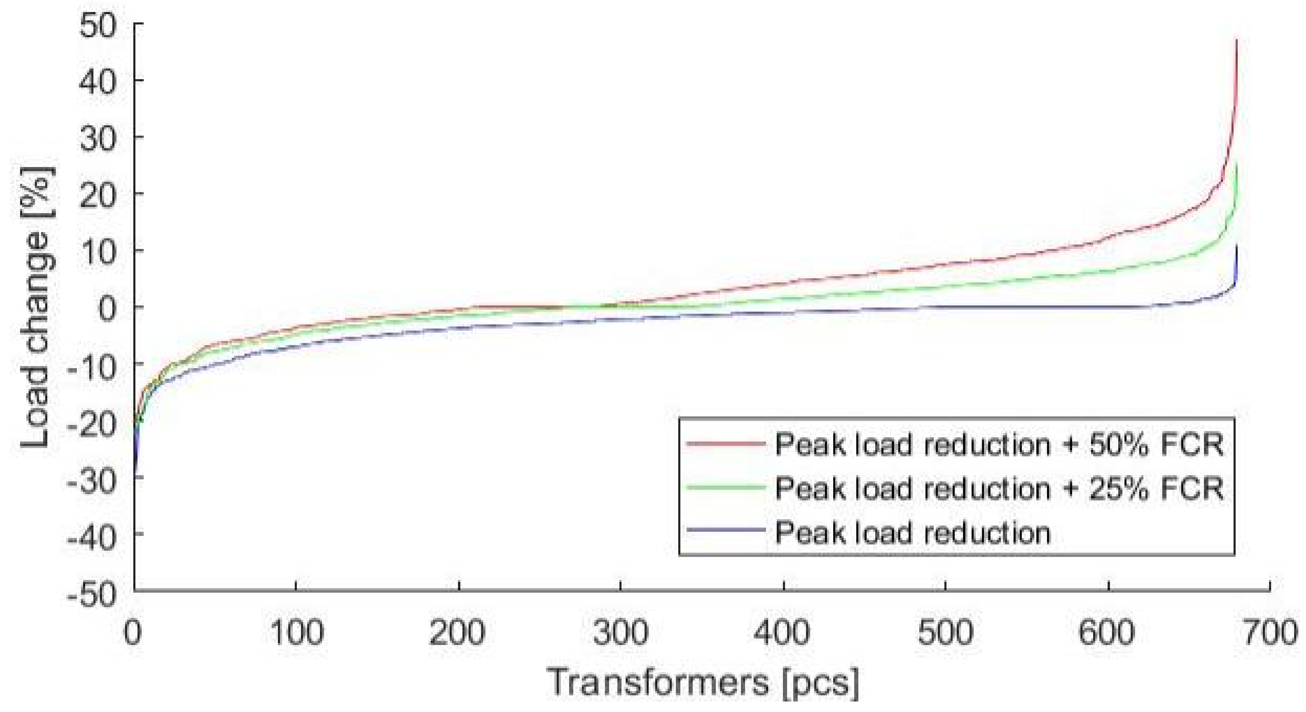

Figure 4. Load changes in distribution transformers compared with the initial load of the transformers.

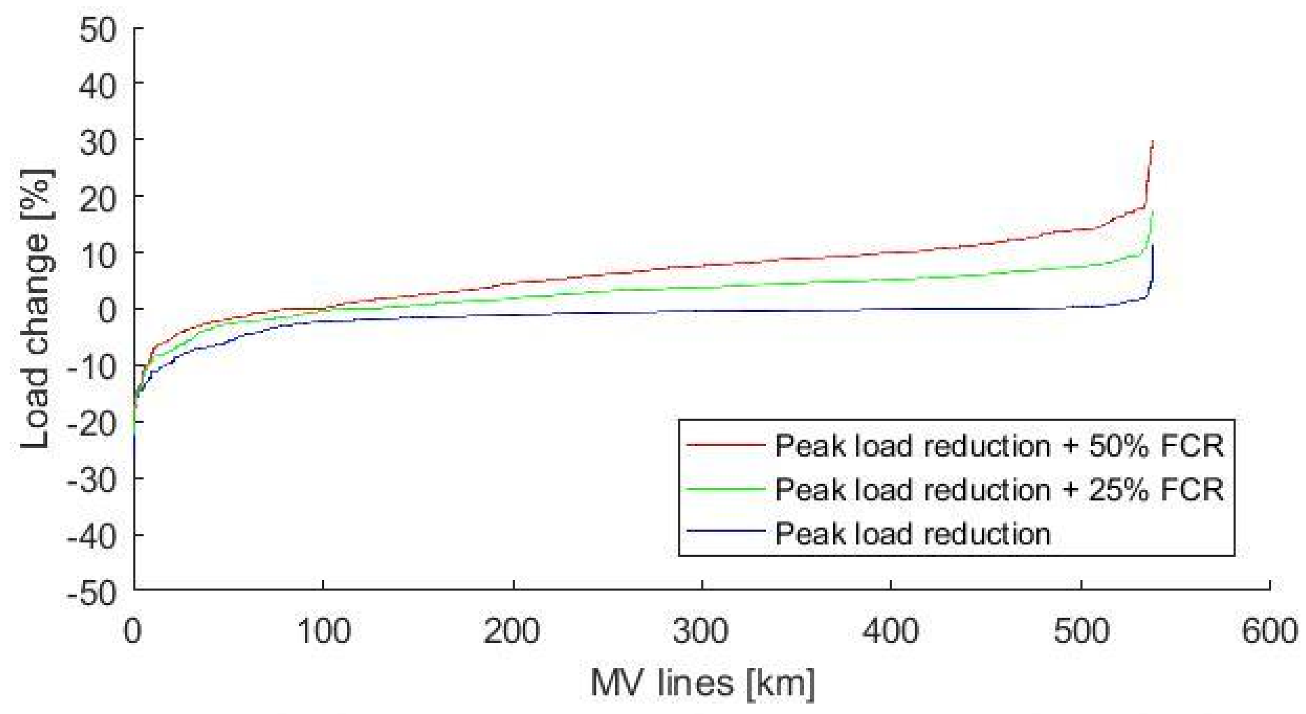

Figure 5. Load changes in MV lines compared with the initial load of the lines.

In general, the results indicate that the loads decrease in the LV side of the network in the case where the BES participates in FCR-N operation, but loads of the transformers and MV lines may increase significantly, especially in MV network. This is a reasonable result because the power-based distribution pricing gives customers incentives to set limits for their power consumption, which leads to levelling of their load behaviour providing significant peak load reduction in the last distribution lines before electricity end-use. The loads do not change considerably in the LV network even if the exploitation of the BES in ancillary service are taken into account, because the power-based tariff restricts customers' peak loads. Nevertheless, the situation is different in the transformers and in the MV network, because the BES power used in the ancillary services cumulates upstream the network contrary to LV network, where the power limitation of a single customer plays a key role.

Figure 6 shows an annual hourly distribution of proportional BES capacities (25% capacity of BES peak hourly power) in the considered distribution system with FCR-N participation. The result shows that most 85% – 100% of the BES are available in frequency containment, but there are some hours with 75% – 80% BES availability. This indicates that there are potential to use the storages simultaneously with ancillary services even the primary function of the BES is peak load reduction.

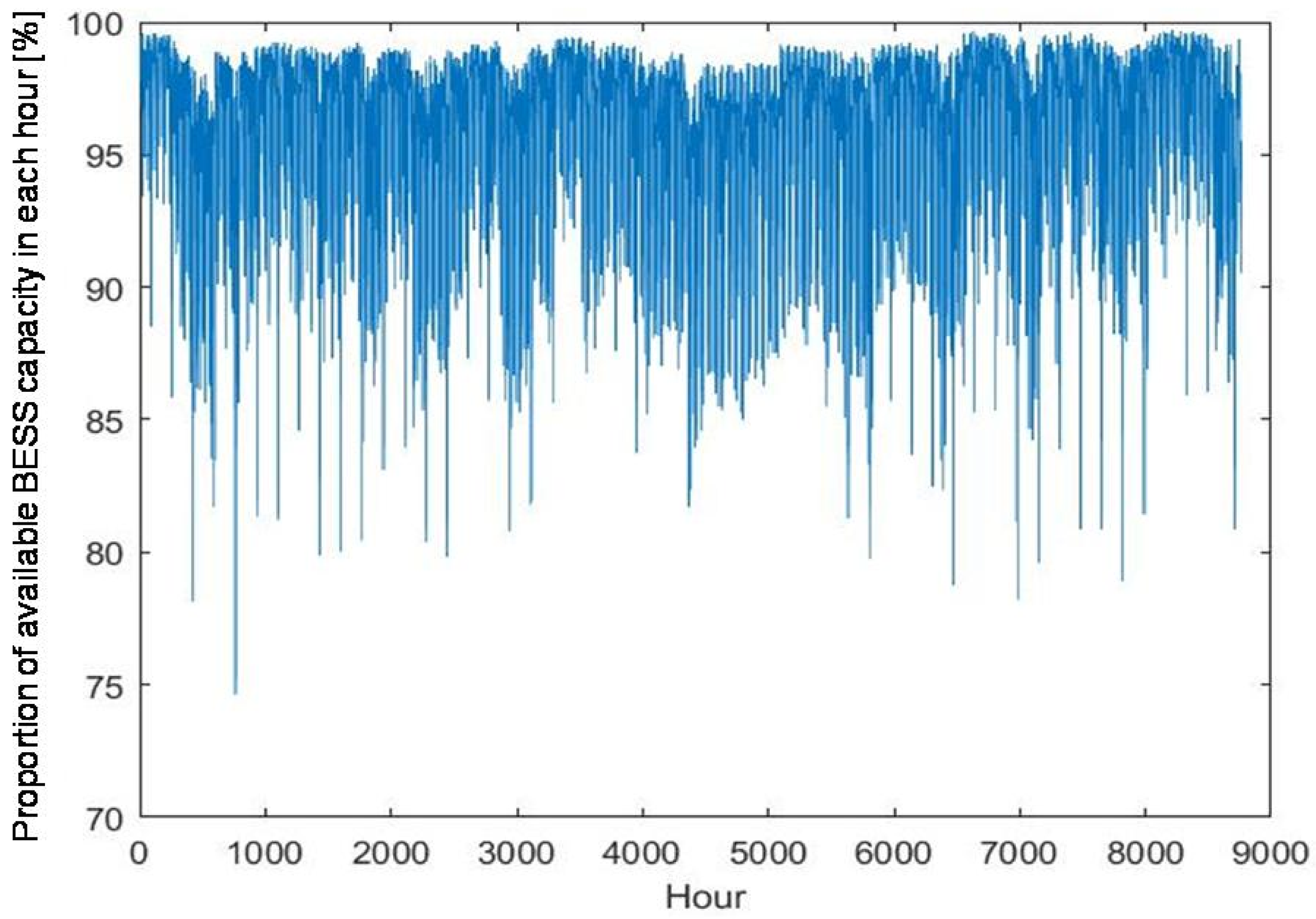

Figure 6. Hourly distribution of available BES capacity (FCR operation with 25% of BES peak hourly power) in the considered network with the power-based price structure

DISCUSSION

The results calculated in the study are based on measured data from actual load points in the distribution networks. Even this provides a good basis for the study, the history of hourly measurements is still relatively short, which means that annual variation is difficult to take into account. In addition, the measured data is with hourly basis, which means that short power peaks are not observed in the study. This may be observed especially on the results of the low-loaded components such as LV lines loaded by a small number of consumers.

In the study the precondition was that energy storages were incentivized by power-based tariffs giving customers an option to reduce their distribution fee by limiting their peak loads. If the energy storages would be used in the system services such as frequency containment, there raises a question; should the BES owners have an opportunity to exceed the peak power limit without a consequence of extra cost for the electricity customer? This would give more available capacity to system control.

In the case study we assumed that the capacity of the BES can be used optimally in peak load reduction operation and FCR operation can be organised similarly with peak load reduction. In reality, the combination of the different goals is not this simple, because at least in the peak load reduction mode there should be capacity to respond to higher demand as is expected. Also, if the full BES capacity is reserved to FCR operation, there is a risk that peak load reduction is endangered, even if the load of the customers could be estimated beforehand with high accuracy.

The effects of distributed solar power systems were not considered in this paper and their combined influence with BES on electricity distribution system. With solar power systems the most challenging for the system can be a situation where the electricity end-user has no load and he supplies full output of solar power system to the electric network. If the electric power system needs up-regulation ($f < 49.95$ Hz) at the same time, the local distribution network can be overloaded.

CONCLUSION

Distributed BES seem to be challenging for the electricity distribution grids if they are used in system ancillary services such as FCR causing a synchronised signal to reserve participants. In the analysed case, the penetration of BES is assumed to be based on a scenario, where the batteries in the network are primarily incentivised by power-based electricity distribution pricing. However, the effects of the BES on the grid seem to depend on the network components grid layer e.g. is the component located in LV or MV network. In the LV network the effects of BES used in ancillary seem to be insignificant, but in the transformer or MV line level a significant proportion of the components may have a considerable load increase. For instance, in FCR operation with 25% of BES peak hourly power even 10% – 20% and in FCR operation with 50% of BES peak hourly power even 20% – 30% load increase, which at least may influence on the dimensioning of the transformers.

The results of the analyses contain much uncertainties, but the study indicates that the effects of the BES on distribution system should be considered in more detail in the future.

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