IMPACT OF RESERVE MARKET PARTICIPATION ON POWER QUALITY OF FLEXIBILITY RESOURCES AND LOCAL ELECTRICITY NETWORKS

Antti HILDÉN, Tampere University, Finland, antti.t.hilden@tuni.fi
Pertti PAKONEN, Tampere University, Finland, pertti.pakonen@tuni.fi
Joni MARKKULA, Tampere University, Finland, joni.markkula@tuni.fi
Eero PAAVILAINEN, Representative of Siemens, Finland, eero.paavilainen@outlook.com
Mikko KETTUNEN, Lempäälän Lämpö Oy, Finland, mikko.kettunen@lempaalanlampo.fi
Pertti JÄRVENTAUSTA, Tampere University, Finland, pertti.jarventausta@tuni.fi
Pekka VERHO, Tampere University, Finland, pekka.verho@tuni.fi

ABSTRACT

The need for demand response grows as more variable, renewable power generation is connected to power systems. The network frequency is supported by various reserve instruments of transmission system operators, for which end-consumer resources are increasingly aggregated. The objective of this paper is to observe how controlling of these resources may have an impact on power quality in a local electricity network. The aggregated resources can be continuously controlled converters or stepwise switched loads. The reserve-based control alters the typical active power profiles of these resources. Power quality measurement data of two FCR-N reserve sites were analyzed with momentary variations and long-term trends. The studied resources were ventilation and air-cooling systems of an office building and two battery energy storages of a microgrid. The measurement data analysis indicates no problems in power quality due to the FCR-N control. However, power quality profiles of the resources are certainly affected. Further analysis of the data is required to determine the consequences of these changes in power quality.

INTRODUCTION

The on-going energy transition and energy crisis in Europe have challenged balance management and security of power systems. Transmission system operators (TSOs) need increasingly complex solutions to ensure power system frequency stability, as inertia-free and variable, renewable power generation continues to gain a larger share in power production. Demand response is generally considered as a key element to enhance power system balance management. Consequently, end-consumer loads are increasingly aggregated for demand response purposes that include reserve markets of TSOs. The monetary incentives of participating in the reserve markets have started to turn also kilowatt-level end-consumer loads into flexibility resources. However, most of the consumer loads are not originally designed for flexibility operation but to provide utility to their user. The realizable reserve capacity depends on costs, technical restrictions and user acceptance. These create uncertainty about the amount and types of loads that will participate in reserve capacity.

The aim of the reserve markets is to support the power system frequency, i.e., balance production and consumption and to react to disturbances. When a flexibility resource is operated for the reserve market purposes that may also have an impact on power quality of the flexibility resource and the local electricity network. The power quality viewpoints of TSO and distribution system operator (DSO) are different: TSO maintains magnitude and stability of the grid frequency, while DSO must supply voltage of a certain quality at the supply terminals of the customer. This has received little attention in literature, even though demand response is a highly researched field. When power quality is considered, more safe and efficient reserve market services can be implemented for the distribution network customers.

It is important to realize that different types of flexibility resources are located in electricity networks that have various electrical characteristics. Flexibility-based control changes the typical consumption profiles of the resources that can also change the power quality disturbances the resources induce. The consequences for power quality can be both positive and negative. It needs to be studied what are the power quality phenomena related to reserve market participation. It seems that concrete evidence of the power quality impact is missing, therefore this paper presents actual measurement data from reserve sites.

The first part of this paper discusses possible power quality phenomena related to reserve instruments based on literature and electrical characteristics of different types of flexibility resources. The latter part of the paper utilizes power quality measurement data from two sites that include ventilation, air-cooling and battery energy storages as flexibility resources for FCR-N reserve. The data are observed to find the impact of the reserve participation to power quality of the resources and the sites.

POWER QUALITY CONSIDERATIONS

A reserve resource in a distribution network can share similar characteristics with solar and wind power plants: Active power of the reserve resource may vary intermittently, the reserve resources are increasingly located in low voltage distribution networks, and the reserve resource can be driven by a power electronic converter in a continuous manner. The reserve resources may also be stepwise type loads. Changes in a converter operating point will impact the current distortion profile and stepwise changes will result in fast voltage changes in the local electricity network. These impacts are the most noticeable in low voltage networks where high impedance reflects the phenomena to voltage.

Some impacts of demand response on power quality have been predicted in literature but further research and concrete evidence are missing. Power quality concerns regarding demand response are presented by Bollen [1] and Zavoda in the final report of CIRED/CIGRE JWG C4.24 [2]. They discuss the following matters: Simultaneous control of multiple same type of loads may reduce harmonic current cancellation, thus distortion in voltage can increase. Voltage unbalance may be introduced due to control of multiple single-phase loads. Damping of a network can decrease if considerable number of resistive loads are disconnected. Stepwise switching of loads for demand response may cause more frequent, and higher magnitude, voltage changes.

The power quality impact of reserve resource control in distribution networks has gotten little attention in the literature. Measurement data analyses are required to identify the critical power quality phenomena caused by the reserve resources. This knowledge can be utilized in distribution network planning and operation, reserve resource control methods, and in designing of power quality monitoring systems. Electromagnetic compatibility of the reserve resources with the local electricity network is based on standardization that needs to be up to date with modern power quality phenomena.

CASE STUDY ANALYSIS

This paper analyses power quality impacts of FCR-N reserve participation with power quality measurements of two sites. The sites are an office building and a microgrid. This section describes the FCR-N reserve, measurements and measurement observations of both sites.

FCR-N reserve

FCR-N stands for Frequency Containment Reserve for Normal operation. In Finland, FCR-N is managed by the national transmission system operator Fingrid Oyj. The capacity accepted to FCR-N must be able to operate symmetrically in the frequency range 49.9-50.1 Hz. In case of load resources, this means the ability to increase and decrease consumption. The capacity is activated continuously with 0.01 Hz dead band based on a local frequency measurement. For 0.1 Hz step change, the maximum capacity must be activated within three minutes. In continuous operation, the activated capacity is linearly proportional to the frequency deviation from 50 Hz. Minimum offered capacity to FCR-N is 0.1 MW. Capacity of several smaller resources can be combined by a flexibility aggregator such as Vibeco Oy in case of the office building in this paper.

Measurement data

Power quality measurements at the sites were performed with eQL Laatuvahti3 meters that measured quantities at 1-second interval. The data are either arithmetic means or root mean squares of the interval according to the appropriate aggregation method. Bandwidth of the meter is 0-2 kHz. The studied measurement quantities are described in Table 1. The meters have been collecting data since May 2018 in case of the office building, and since September 2020 in case of the microgrid. The utilized data period for the office building is May 2018 – September 2022. The microgrid is analyzed on one day from 2022. The publication [3] describes in detail the data collection platform of the measurements.

Table 1. Measurement quantities used in the case analyses.

Quantity and unit	Description
f (Hz)	Fundamental frequency
U_{L1} (V)	Phase voltage of L1 in bandwidth 0-2 kHz
U_{12} (kV)	Line-to-line voltage between phases L1 and L2 in bandwidth 0-2 kHz
P (kW)	Total three-phase active power in bandwidth 0-2 kHz
Q_1 (kvar)	Total three-phase fundamental frequency reactive power for fundamental frequency component
$I_{TD,L1}$ (A)	Total distortion of current of phase L1 in bandwidth 0-2 kHz including interharmonics
$TD_{I,L1}$ (%)	Total distortion of current of phase L1 in percentage of fundamental frequency component in bandwidth 0-2 kHz including interharmonics
$TD_{U,L1}$ (%)	Total distortion of voltage of phase L1 in percentage of fundamental frequency component in bandwidth 0-2 kHz including interharmonics
T (C)	Outside temperature (instant value)

Office building

The office building, called Kampusareena, is located at Tampere University campus in Finland. Ventilation and air-cooling systems of the building are controlled as a part of the FCR-N reserve. In ventilation, the frequency converters that drive fans are controlled in a continuous manner. In air-cooling, the electric motors of the compressors of two cooling units are controlled in a stepwise manner. In addition to participating in FCR-N, these resources must maintain a good air quality in the building. Maximum active power of the ventilation during the study period has been 138 kW. Similarly for the air-cooling units 1 and 2 the powers are 145 kW and 175 kW, respectively. The nominal electrical powers of the cooling units are: 170 kW and 226 kW, and they have four and six compressors, respectively. The frequency converters and the compressors are three-phase loads, therefore three-phase quantities are considered for power and one phase (L1) for voltage magnitude and total distortion of current and voltage. One must also realize that COVID-19 has influenced the use of the office building since March 2020 when the university campus was closed, after which the students and personnel have not returned to the campus completely due to changed studying and working methods. The electricity network and measurement points of the office building are presented in Figure 1. The office building is connected to a 20 kV network with two transformers that feed two main distribution boards. The ventilation and air-cooling units are supplied by the same main distribution board. Also, a solar power plant supplies the feeder of the ventilation system. This is compensated in the main distribution board and ventilation feeder measurements of active power and fundamental frequency reactive power using the solar power plant measurement to study the actual consumption. The office building has a strong network the short-circuit current being over 10 kA at the main distribution board.

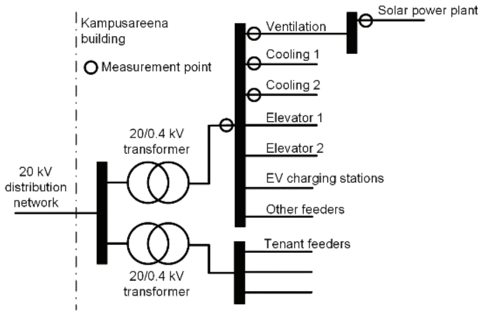

Figure 1. The main electricity distribution and measurement points of the office building.

Momentary power quality

Power quality impact of the FCR-N participation of the office building resources is studied first with a closer look to momentary variation, and then with long term trends of the complete measurement period. Figure 2 demonstrates how active power (P) profile of the ventilation changes when the FCR-N control is applied. Both days of the figure are from a winter season but the later day (2nd of December) has the ventilation participating in the reserve. The FCR-N control has changed stepwise P to constantly varying consumption, even during night time.

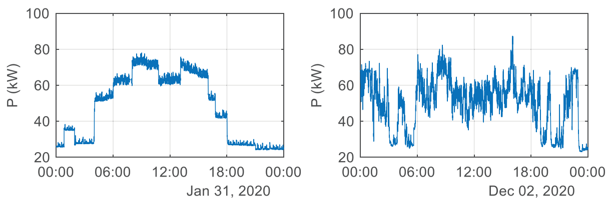

Figure 2. Ventilation before (31st of January) and after (2nd of December) being part of the FCR-N reserve.

Fundamental frequency reactive power (Q_1) and total distortion of current in amperes ($I_{TD,L1}$) and as percentage ($TD_{I,L1}$) of the ventilation are presented in Figure 3 where also fundamental frequency (f), control signal and P of the ventilation are shown. It can be observed that f, control signal and P are strongly correlated. This indicates that the ventilation has been controlled based on the frequency deviation according to FCR-N. When f is below 50 Hz the control is negative and consumption is reduced, and vice versa. This variation has a clear impact to Q_1 which gets increasinly capacitive when consumption is reduced. It is also evident that $I_{TD,L1}$ is positively proportional to the consumption.

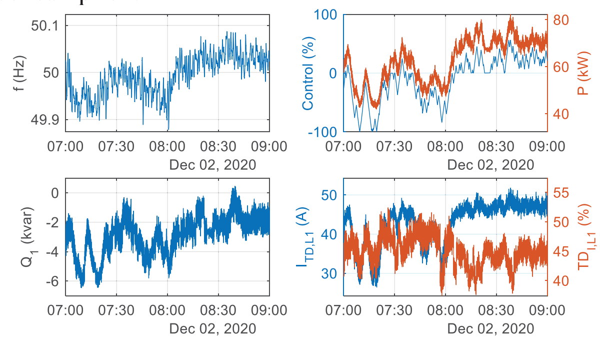

Figure 3. Ventilation during the FCR-N control.

The operation of the air-cooling system was found difficult to associate with the participation to FCR-N using the measurement data. This may be because of the stepwise switching of the compressors that cannot be controlled continuously as the ventilation. However, the cooling units are a part of the aggregated reserves of the building. Figure 4 demonstrates the changes of P of the two cooling units. The changes are a bit over 20 kW, instant and can happen multiple time in an hour.

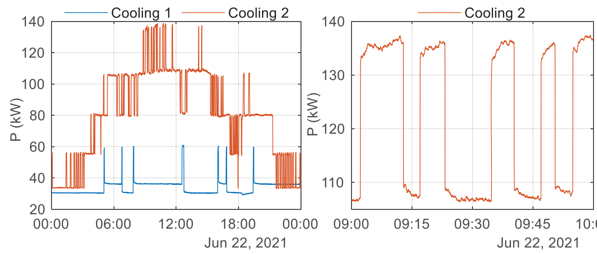

Figure 4. Operation of the two air cooling units.

Trends of power quality

The commisioning date of the FCR-N participation is known for the office building and the measurements include data of around two years before and after the commissioning. Therefore, trends of the data can be studied to find power quality impact of the FCR-N control. First, fundamental frequency (f) and activated FCR-N volume in the Nordic synchronous system are observed in Figure 5. The trends are weekly 5th and 95th percentiles of f with FCR-N maximum capacity limits, weekly standard deviation of f (std_f), and weekly mean of the activated FCR-N volume. Positive activation means up-regulation of frequency that requires consumption reduction. The FCR-N control was commissioned in September 2020. During summer 2020 the measurements were interrupted due to the commissioning. The trend indicates that the activated reserves in the Nordic synchronous system have decreased after the beginning of 2021, and that deviation of f has is getting lower.

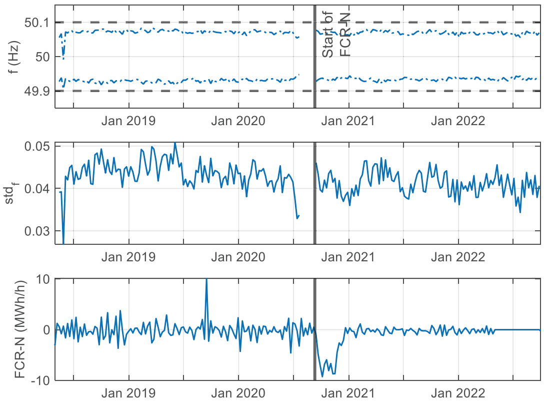

Figure 5. Trends of fundamental frequency (f), standard deviation of f (std$_f$) and activated FCR-N volume.

Power quality at the office building is considered with trends of the same time period. The trends of active power (P), fundamental frequency reactive power (Q_1) and total distortion of current ($I_{TD,L1}$) include weekly mean or rms, and 5th and 95th percentile for the ventilation, cooling units and the main distribution board that supplies them. Additionally, outside temperature trend is presented for the main distribution board to demonstrate the temperature dependence of the resources. The trends can be observed in Figures 6-8. The main finding from the trends is that little considerable changes are observed after the start of the FCR-N participation. The trends have annual variation but clear development due to the FCR-N control cannot be deduced. One may say that for the summers 2021 and 2022 larger variation of $I_{TD,L1}$ is noticed for the air-cooling units. The measurement points of the office building have very similar voltage because the measurements are from the same busbar at the main distribution board. Voltage trend at the office building is presented in Figure 9 that contains weekly rms of L1 phase voltage magnitude (U_{L1}), standard deviation of voltage ($std_{U,L1}$) and total distortion of voltage ($TD_{U,L1}$). Again, no clear trends can be recognized from the figure. However, summer seasons, especially summer 2021, have elevated $std_{U,L1}$ that may originate from the operation of the cooling units in summer. During the same periods, lowered voltage magnitude can be detected. High peaks in $std_{U,L1}$ and $TD_{U,L1}$ are due to a measurement error during an interruption in the measurement.

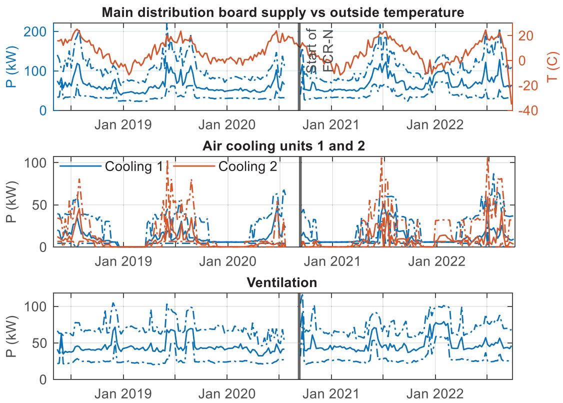

Figure 6. Trend of active power (P) for the main distribution board, air-cooling and ventilation.

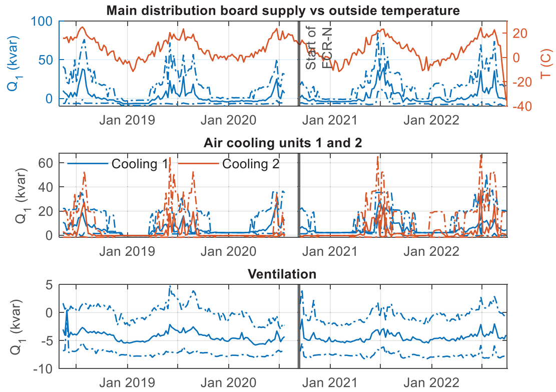

Figure 7. Trend of fundamental frequency reactive power (Q_1) for the main distribution board, air-cooling and ventilation.

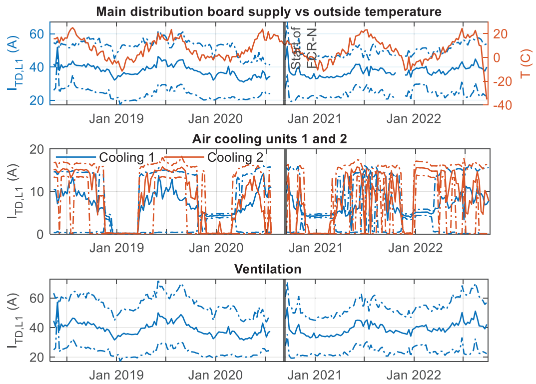

Figure 8. Trend of total distortion of current ($I_{TD,L1}$) for the main distribution board, air-cooling and ventilation.

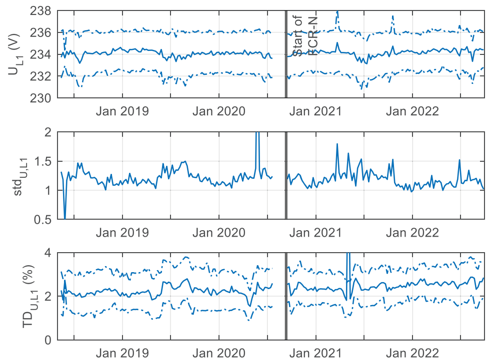

Figure 9. Trend of voltage magnitude (U_{L1}), standard deviation ($std_{U,L1}$) and total distortion ($TD_{U,L1}$) at the office building.

Microgrid

The microgrid has been established by Lempäälän Energia Oy in LEMENE project to Lempäälä in Finland. Two battery energy storages of the microgrid can be driven in parallel for the FCR-N reserve. The battery energy storage 1 has maximum power of 1.6 MW and 1.3 MWh energy storage. For the battery energy storage 2, the specifications are 2.4 MW and 1.6 MWh, respectively. The battery energy storages must be ready to form an islanded network if conditions in the local public distribution network require so. In normal operation, the microgrid is connected to the local public distribution network. The microgrid has a 20 kV underground cable ring network and each of the resources have their own transformer. The main electricity distribution of the microgrid and the studied measurement points are illustrated in Figure 10.

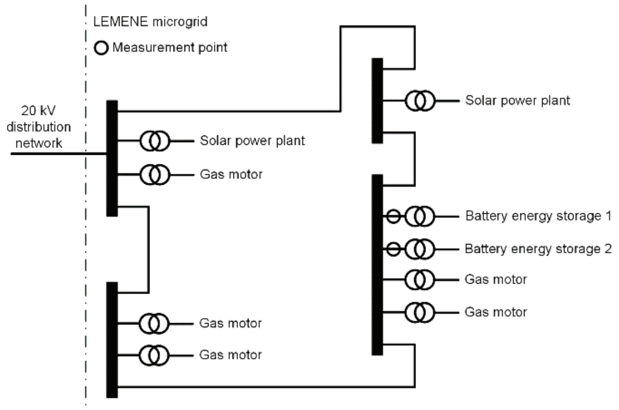

Figure 10. The main electricity distribution and measurement points of the microgrid.

The battery energy storages are observed only on one occasion of five minutes in this paper. During that time, it is evident that active power (P) of the battery energy storages follows the deviation of fundamental frequency (f) as can be seen in Figures 11 and 12, which indicates participation in the FCR-N reserve. Positive P is charging of the battery energy storage.

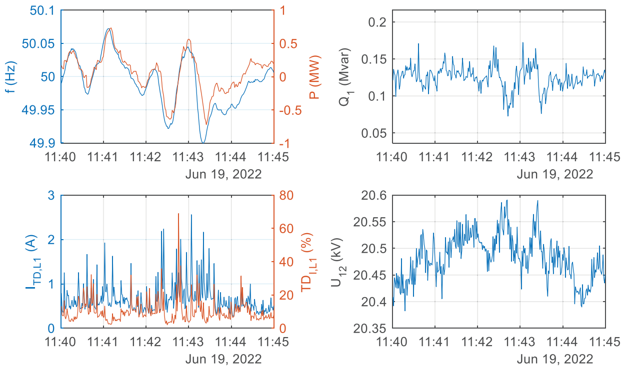

Figure 11. The battery energy storage 1 during the FCR-N control.

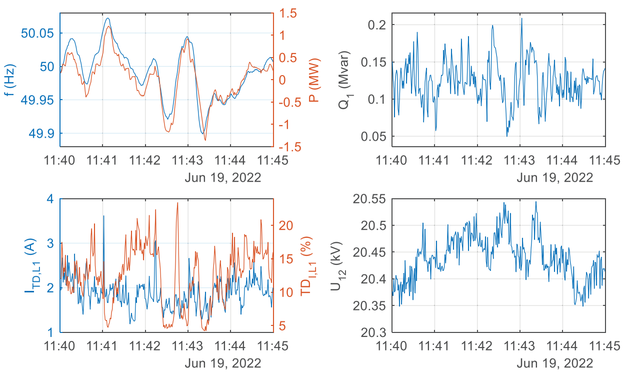

Figure 12. The battery energy storage 2 during the FCR-N control.

The battery energy storages have different manufacturers that may be seen in differences in total distortion of current ($I_{TD,L1}$ and $TD_{I,L1}$). The battery energy storage 1 has lower base level of $I_{TD,L1}$ but higher peaks that occur when P changes. Relatively small magnitude and variation of inductive Q_1 is observed for both battery energy storages. Also, line-to-line voltage (U_{12}) has minor changes in the magnitude. If the continuous control of the battery energy storages is compared with the ventilation of the office building, two differences are found: The frequency converters of the ventilation are assumed to have passive rectifiers contrary to the battery energy storages that can control separately P and Q_1 drawn from the network. Secondly, P of the ventilation always varies on the consumption side but P of the battery energy storages changes direction frequently which means operation in small power momentarily.

CONCLUSIONS

In this paper it is considered that reserve market resources can have similar characteristics to renewable power generation: intermittent operation based on fundamental frequency, driven by power electronic converters and be located in a low voltage network. The FCR-N resources that were observed with the power quality measurement data can cause different power quality phenomena as the air-cooling uses the stepwise controlled compressor electric motors, the ventilation has passive rectifiers in the frequency converters and the battery energy storages have active grid-connected converters with constantly changing direction of active power. It was evident that the FCR-N control can drastically change the active power profile of a resource, consequently power quality is affected. However, the trends of fundamental frequency reactive power, total distortion of current and voltage, and voltage magnitude indicated little changes after the commissioning of the FCR-N control. This may be an encouragement for the aggregation of reserve resources. Additional analysis with voltage and current harmonics and flicker index data is required to determine consequences of the drastically changed active power profiles of the resources.

ACKNOWLEDGMENTS

We are thankful for University Properties of Finland Ltd and Lempäälän Energia Oy for enabling the measurements in Kampusareena and in the LEMENE microgrid, and for Siemens Oy for providing the flexibility control data.

REFERENCES

[1] M. Bollen et al., 2017, "Power quality concerns in implementing smart distribution-grid applications", *IEEE Trans. Smart Grid*, vol. 8, no. 1, pp. 391–399.

[2] F. Zavoda et al., 2018, "Power quality and EMC issues associated with future electricity networks - Final report", CIGRE/CIRED JWG C4.24.

[3] A. Hildén et al., 2022, "A data collection and supplementary control platform of a modern building for smart energy applications", *Sustainable Energy, Grids and Networks*, vol. 32, p. 100928.