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Development and Application of KPIs for the Evaluation of the Control Reserve Supply by a Cross-border Renewable Virtual Power Plant

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Abstract: In an increasingly decentralised energy system with a rising share of fluctuating renewable energy sources, such as wind energy and photovoltaics (PV), the importance of virtual power plants (VPP) for the provision of ancillary services is growing. Transmission system operators (TSOs) impose stringent requirements on the reliability and accurate controllability of power plants that are susceptible to qualify for control reserve provision. It needs to be discussed whether these requirements have to evolve to enable the participation of renewables in control reserve markets. As part of the REstable research project, an innovative ICT infrastructure was set up for linking German and French wind and PV farms in a transnational VPP. Key performance indicators (KPIs) derived from technical requirements of the German TSOs are proposed and applied to quantify the quality of control reserve provision by the VPP in physical field tests.

Keywords: Virtual Power Plants; System Architecture; Control Reserve; Requirements; KPIs

1 Introduction

In the entire synchronous area of the ENTSO-E (European Network of Transmission System Operators for Electricity), the grid frequency must remain within precisely defined limits at all times in order to avoid consumer disconnections and grid breakdowns [Sw06]. For this reason control reserve is used to keep the grid frequency stable at 50 Hertz. The TSOs have the responsibility to organise markets for the provision of positive and negative control reserve in three different qualities (Frequency Containment Reserve, automatic and manual Frequency Restoration Reserve) in their control zones and to apply them at short notice if necessary [Eu17]. The fluctuations and forecasting errors in wind and PV generation will increase the need for flexibility and reserves in the European electricity grid with the rising share of renewable energies [Ac15]. The aggregation of renewable power plants can reduce their production uncertainty and enables aggregated plants controlled via a VPP to submit control reserve bids based on e.g. probabilistic forecasting [CMK18]. The general capabilities of renewable energies as well as control mechanisms and technical challenges for providing ancillary services have already been reviewed and discussed e.g. in [ADA18], [HSS16] and [Dí14]. Moreover, the

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physical ability of wind energy and photovoltaics to provide control reserve within a VPP has already been demonstrated in former research projects of Fraunhofer IEE [Fr14], [Fr17]. In these projects the control of energy units was realized via the in-house software for a central control system «IEE.vpp».

A new challenge is to build up the ICT connection for a various set of power plants from different manufactures and operators in different countries and to overcome the country specific regulatory obstacles for a central control of wind and PV farms. Last, it is a challenge to prove the fulfilment of the strictest requirements for the provision of Frequency Containment Reserve (FCR) with fluctuating renewables. The German-French-Portuguese project «REstable» takes up these challenges to improve renewable-based system services by better cooperation of the European control zones.

The objective of this work is to analyse the quality of control reserve provided by fluctuating energies in an exactly quantifying and comparable way and to compare the results for the currently valid technical requirements with the newly published prequalification conditions by the German TSOs [Ge18b]. Physical control power field tests carried out with IEE.vpp are evaluated with the help of a key figure system that is developed within the context of the REstable project. The mathematical formulation of the KPIs is derived from the requirements in the publicly accessible documents of the German TSOs. With the use of Python automated evaluations are visualized.

Since FCR operates across countries in the entire network system and places the greatest requirements on control speed and technology, the focus of this work is on the execution and evaluation of FCR field tests. The FCR field tests in the REstable project explore possible pre-qualification frameworks for renewable energies, as there are still European wide barriers to entry in frequency-regulation services markets [Bo18]. In Germany it is neither possible to operate on FCR markets with fluctuating energies [Ge18d] nor to use control zones crossing or even cross-national pools of power plants for providing control reserve [Eu17]. With regard to harmonized European power markets and the growing importance of PV and wind energy for the system stability [Bu15], the investigation of the ability of renewable energies performing FCR is a relevant future topic.

2 Related Work

The comprehensive method of this work is a new approach to evaluate ancillary services by aggregated renewable power plants in physical field tests automatically.

The system architecture of a VPP composed of distributed energy resources with the capability to provide grid frequency support has already been shown in [Es17], though the case study results were based on simulations instead of physical field tests. A methodological challenge for developing performance indicators for grid operations is how to translate laws or regulatory frameworks into equations. Requirements analyses based on technical grid codes have been presented in [Dí14], [HSS16], [LER12] and [PVG17], whereby [LER12] and [PVG17] also develop specific derived key figures to measure the system stability, the availability or the deviations from a certain set point, for example. [LER12] defines KPIs of control reserve provision integrating the dynamics of the response of the balancing provider. However, none of these authors has developed one global KPI that allows to evaluate the performance quality respectively the fulfilment of the grid requirements at a glance. Moreover, the evaluations are either based on simulations [HSS16], [PVG17] or do not consider variable renewable production units [LER12].

Whereas this work proposes a method to evaluate automatically real physical control reserve field tests of renewable power plants within a VPP based on one main KPI which is derived from the technical requirements of the existing grid codes.

The system architecture for the control reserve field tests is presented in section 3.1, and the methodology for the performance evaluation in section 3.2.

3 Proposed Methods

3.1 System Architecture for Building a Transnational VPP

The system architecture of the VPP (see Fig. 1) consists of different major components that are described more in detail below. The central component of the VPP is the control system, which coordinates all FCR processes.

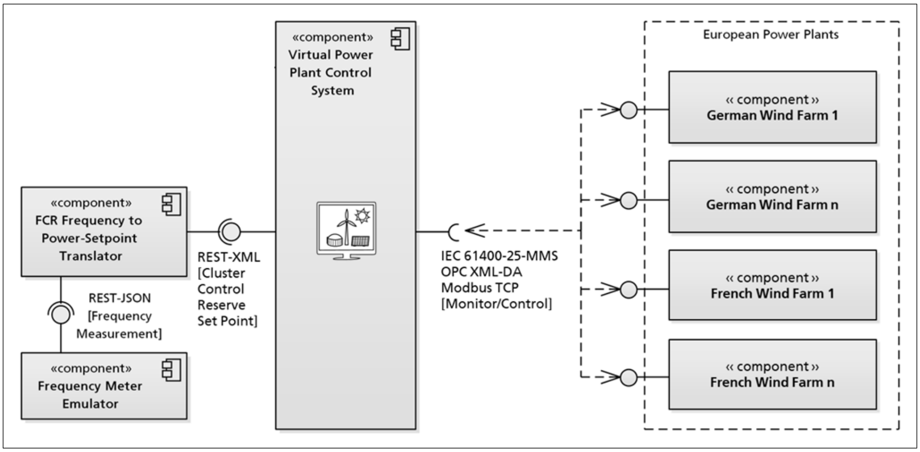

Fig. 1: REstable field test system architecture for FCR

On the customer side, the power plants can be connected via various interfaces. Within the project, the different power plants were connected via IEC 61400-25-MMS, OPC XML DA and Modbus TCP. *IEC 61400-25-MMS* is a communication standard for a uniform information exchange for monitoring and controlling wind power plants and was developed by the technical committee «Wind energy generation systems» (IEC TC 88) [MTH09]. It is based on IEC 61850, which is used for communication in substation automation. The standard defines the components of a wind turbine in a manufacturer-independent environment and serves to exchange the information provided by the components [Le08]. *OPC XML-DA* was released by the OPC foundation and relies on the OPC DA server based on COM/DCOM technology. Due to some limitations of that technology like platform dependency and communication issues, the OPC foundation decided to further develop the specification based on a SOAP (Simple Object Access Protocol) web service via HTTP (Hypertext Transfer Protocol) [HY10]. *Modbus TCP* has become a standard communication protocol for connecting industrial devices in a vendor-neutral way. It is commonly used in SCADA systems for communication with programmable logic controllers (PLCs) [MNK14]. All three protocols define the data points and the way to communicate. In addition, IEC 61400-25-MMS defines a data model for a uniform information exchange for monitoring and control. This data model is vendor-specific in OPC XML-DA and Modbus TCP.

The architecture used in the project differs from a current FCR architecture. In real operation, each power plant would have its own frequency meter. The active power response would be activated autonomously by each power plant based on local frequency measurement [Sw06], [Co14]. The control system would only be responsible for the distribution of the shares of control reserve provision, which are disaggregated for each participating power plant. In contrast to this, in the architecture for control reserve field tests it is useful to perform the frequency measurement centrally at the control system to avoid installation expenses for several power plants. For the REstable project's field test purpose the system architecture has been modified to the extent that a frequency meter emulator that emulates a frequency signal of the grid is used instead of a central frequency measurement. The values are read in via a csv-file and are provided to the control system via a REST-JSON interface. It has the advantage that a common and defined frequency curve can be used for all power plants and for each test in order to be able to build reproducible and evaluable field tests. For the FCR field tests an FCR bid is set manually in the VPP control system, the amount of which depends on the weather conditions for wind and solar.[3] The conversion of the given grid frequency into an active power target for the tests is performed by a component called «Frequency to Power-Setpoint Translator», which is connected to the frequency emulator via a REST-JSON interface and to the VPP control system via a REST-XML interface. The converter calculates the active power reserve set point based on the frequency using the frequency power curve (see Fig. 2). The calculated amount of target activation is send to the VPP control system. The target active power is disaggregated for the participating power plants by the VPP control system. This disaggregation takes into account the available active power (AAP) and the state of each power plant. The result of the disaggregation is a necessary active power reduction for each power plant, which should be realized to

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[3] In the target state of the system architecture, a connected trading tool would be responsible to submit accepted FCR offers to the control system.

provide the required amount of FCR.

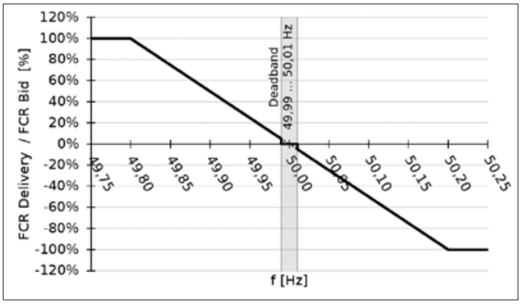

Fig. 2: FCR power frequency characteristic [Ge14]

The following subchapter presents the evaluation methodology for FCR field tests, including the requirements analysis, the development of KPIs and the Python model.

3.2 Performance Evaluation of Control Reserve Supply

Requirements Analysis of FCR

The FCR is activated non-selectively and in solidarity throughout the ENTSO-E network. It has to be provided symmetrically in positive and negative direction and must be available for up to 15 minutes within 30 seconds in case of activation. [Co14], [Sw06]

The following table contains the most relevant requirements for the KPI evaluation that are based on the official German TSO's documents.

ID	Short Title	Description	Source
FCR_01	Provision time slice	The VPP must provide the contracted FCR for the time slice of one week (Mo 0:00 to Su 24:00).	[Bu11]
FCR_02	Provision availability	The VPP must ensure a 100 % availability of contracted power during the whole provision period.	[As03]
FCR_03	Activation time	The VPP must activate the required power reserve within maximal 30 seconds.	[As03]
FCR_04	Duration of activation	The VPP must be able to deliver the contracted FCR for at least 15 minutes.	[As03]
FCR_05	Over- and underfulfillment	The VPP must ensure a maximal overfulfillment of the maximum value of (5 MW, 20 % of the set point) and avoid any underfulfillment.	[Ge13]

Tab. 1: German FCR requirements

The amendment of the FCR requirements as in [Ge18b] leads to some modified and as well some additional requirements, which are presented in Tab. 2.

ID	Short Title	Description	Source
FCR_06	Power change areas	The period after a set point change is separated into a power change area (0...30 s), a transient area (30...90 s) and a stationary area (90...n s).	[Ge18b]
FCR_07	Gradient	The VPP has to activate the FCR evenly, i.e. the first 50 % in the first 15 seconds and the last 50 % linearly in the next 15 seconds.	[Eu17], [Ge18b]
FCR_05	Over- and under-fulfillment	An over- and underfulfillment of 20 % (10 %) of the set point is permitted resp. of 30 % (20 %) is tolerated during the transient (stationary) area.	[Ge18b]
FCR_08	Permitted / tolerated corridor	The VPP must ensure at least 95 % of the values to be within the permitted corridor and maximal 5 % within the tolerated corridor.	[Ge18b]

Tab. 2: Amendment of German FCR requirements

A supporting visualization of the requirements regarding the activation times and the tolerance corridors is illustrated in Fig. 3.

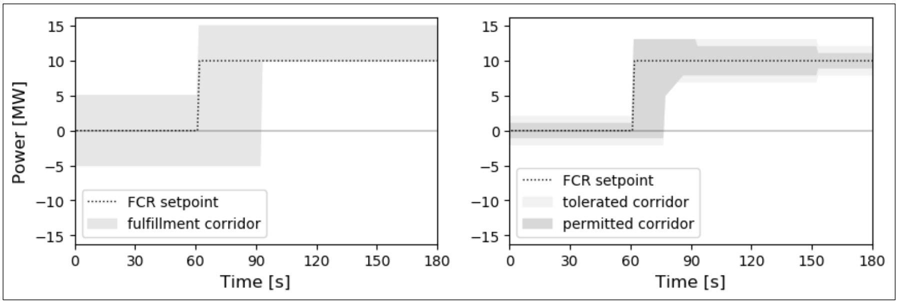

Fig. 3: Limits of fulfilment corridor (left) and limits of permitted and tolerated corridor (right)

Key Performance Indicators

The following time series can directly be exported from the VPP to use them for further calculations.

- Active power $P(t)$
- Available active power $aap(t)$
- FCR bid (provision of ordered control reserve capacity)
  - positive $prov_{ord,pos}(t)$
  - negative $prov_{ord,neg}(t)$
- Set point control reserve (activation call) $s(t)$

- Real time schedule $rts(t)$

$$rts(t) = aap(t) - prov_{ord,pos}(t) \tag{1}$$

- Actual value control reserve (activation) $av(t)$

$$av(t) = P(t) - rts(t) \tag{2}$$

In this work, one exemplary KPI, the activation quality, is presented since it is the best comparable one. The following time series are calculated to further calculate the KPI.

- Acceptance channel

The following formulas for the upper limit $uac_{FCR}(t)$ and lower limit $lac_{FCR}(t)$ of the acceptance channel consider the requirements for control reserve (*FCR_03* in Tab. 1) and are adapted to official public formulas of the German TSOs as in [Ge18a].

$$uac_{FCR}(t) = \max\{s(t-31), \dots, s(t)\} \tag{3}$$

$$lac_{FCR}(t) = \min\{s(t-31), \dots, s(t)\} \tag{4}$$

According to the new prequalification requirements (see *FCR_07* in Tab. 2), the upper limit $uac_{FCR}(t,j)$ and lower limit $lac_{FCR}(t,j)$ of the acceptance channel for FCR are now determined by a reaction time $T_{react} = 15\,s$ and a certain gradient $g(t)$ after each timestamp t_{change} with a set point change. The equations below refer to the formulas for the calculation of tolerance limits in [Ge18c].

$$g(t) = \frac{|s(t) - s(t-30)|}{30\,s} \tag{5}$$

$$t_{change} \in \{t, s(t) \neq s(t-1)\} \tag{6}$$

For $\forall\, j \in \{t_{change}, \dots, t_{change} + 2 * T_{react}\}$:

$$uac_{FCR}(t,j) = \begin{cases} s(t), & s(t) \geq s(t - 2 * T_{react}) \\ s(t - T_{react}), & [s(t) < s(t - T_{react})] \wedge [j \leq (t_{change} + T_{react})] \\ s(t - 2 * T_{react}) - (j - t_{change}) * g(t), & s(t) < s(t - 2 * T_{react}) \end{cases} \tag{7}$$

$$lac_{FCR}(t,j) = \begin{cases} s(t), & s(t) \leq s(t - 2 * T_{react}) \\ s(t - T_{react}), & [s(t) > s(t - T_{react})] \wedge [j \leq (t_{change} + T_{react})] \\ s(t - 2 * T_{react}) + (j - t_{change}) * g(t), & s(t) > s(t - 2 * T_{react}) \end{cases} \tag{8}$$

- Fulfillment corridor / tolerated and permitted corridor

The upper and lower limit of the acceptance channel is extended by certain tolerances which are defined in requirement number FCR_05 in Tab. 1 and Tab. 2. The calculation of the upper and lower limits of the tolerance corridors is performed by a Python based analysis framework and leads to the visualization in Fig. 3. The formula symbols for the different corridors are summarized in Tab. 3.

Corridor	Upper limit	Lower limit
fulfillment corridor	$ufc(t)$	$lfc(t)$
permitted corridor	$upc(t)$	$lpc(t)$
tolerated corridor	$utc(t)$	$ltc(t)$

Tab. 3: Formula symbols upper and lower corridors

In order to determine the total activation quality, the share of values within the fulfilment corridor respectively within the tolerated and permitted corridor is measured.

- Values within fulfillment corridor / tolerated and permitted corridor

$$av_{fulfillment}(t) = \begin{cases} true, & lfc(t) \leq av(t) \leq ufc(t) \\ false, & else \end{cases} \tag{9}$$

$$av_{permitted}(t) = \begin{cases} true, & lpc(t) \leq av(t) \leq upc(t) \\ false, & else \end{cases} \tag{10}$$

$$av_{tolerated}(t) = \begin{cases} true, & ltc(t) \leq av(t) \leq utc(t) \\ false, & else \end{cases} \tag{11}$$

- Share of values within fulfillment corridor / tolerated and permitted corridor

$$av_{fulfillment,true} = \frac{1}{n}\sum_{i=1}^{n} \mathbb{1}\left\{av_{fulfillment_i}, av_{fulfillment_i} = true\right\} \tag{12}$$

$$av_{permitted,true} = \frac{1}{n}\sum_{i=1}^{n} \mathbb{1}\left\{av_{permitted_i}, av_{permitted_i} = true\right\} \tag{13}$$

$$av_{tolerated,true} = \frac{1}{n}\sum_{i=1}^{n} \mathbb{1}\left\{av_{tolerated_i}, av_{tolerated_i} = true\right\} \tag{14}$$

- Activation quality

The activation quality corresponds to the share of values within the fulfilment corridor. For the new requirements, it is the share of values within the permitted corridor plus max. 5 % of the measured values within the tolerated corridor (see *FCR_08* in Tab. 2).

$$quality_{old}(\%) = av_{fulfillment,true} * 100 \tag{15}$$

$$quality_{new}(\%) = \left(av_{\mathrm{permitted},true} + \max\{av_{tolerated,true}, 0.05\}\right) * 100 \tag{16}$$

All formulas can be calculated separately for times of positive FCR activation, negative FCR activation and zero FCR activation. This might be interesting to investigate misbehaviour of the power plants in certain situations, because from a technical point of view it is another challenge to provide positive control power compared to negative.

Python Model for Automatic KPI Evaluations

The evaluation in Python can be generated after each field test. The modular structure of the Python model is described below and is illustrated in Fig. 4.

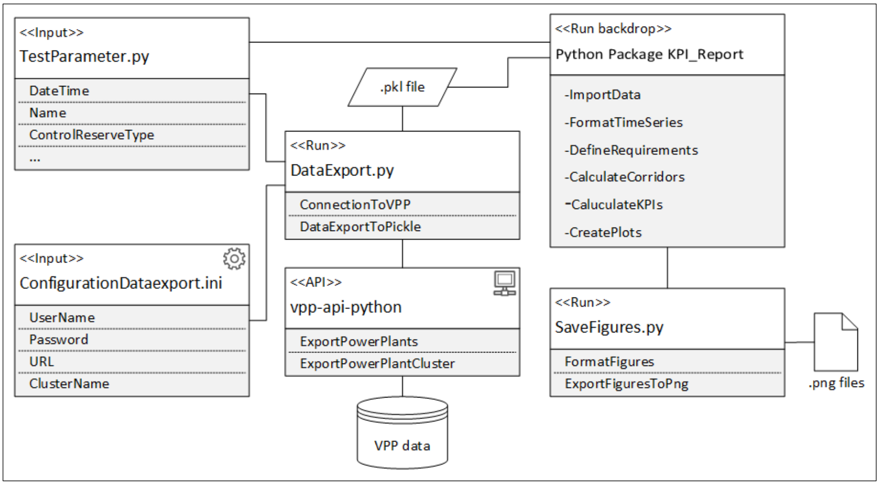

Fig. 4: Python model for the automatic FCR test evaluation

The Application-Programming-Interface (API) *vpp-api-python* allows the access to the VPP data. The configuration file *ConfigurationDataexport.ini* contains connection and configuration details for the VPP data export. In the script *TestParameter.py* some test and wind farm specifics have to be defined by the user. The script *DataExport.py* reads the information of the configuration file and the test parameters. It exports defined time series via the API from the VPP data and safes it in a pickle (.pkl) file which is useful for archiving large amounts of data in a Python conform data format. The different scripts in the Python package *KPI_Report* have functions to import the time series from the pickle file, to convert it to pandas data frames, to calculate the tolerance corridors and the KPIs and to create plots for the visualization of the evaluations and time series. The script

SaveFigures.py activates the Python package *KPI_Report* backdrop and finally exports the produced plots of time series and evaluation diagrams to PNG files.

In the next chapter, a case study for executing and evaluating FCR field tests with application of the described methods is presented.

4 Case Study

4.1 Performing Transnational Control Reserve Tests

For the control reserve tests, the frequency emulator simulates a frequency deviation in the grid. First, a reduction of the grid frequency of 200 mHZ is simulated for 15 minutes (minutes 20 to 35 in Fig. 5) and an increase of the grid frequency of 200 mHz is simulated between minutes 50 and 65. This is analogical to the FCR model protocol that has to be performed in Germany to prove FCR ability [Ge18b]. The stepwise activation of control reserve enables a clear observation of the active power response of the VPP. According to the frequency power characteristic in Fig. 2, a frequency deviation of +/- 200 mHz corresponds to the complete activation of the FCR bid.

An exemplary reaction of the power plants to the FCR bid and the activated FCR is shown in Fig. 5, that visualises the time series active power $P(t)$, available active power $aap(t)$ and the real time schedule $rts(t)$.

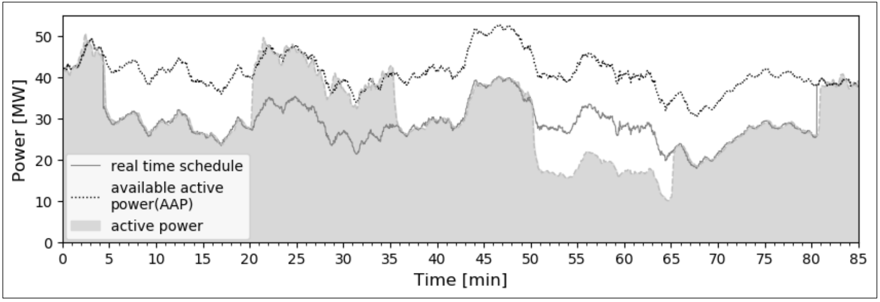

Fig. 5: Physical reaction of a wind farm cluster to FCR set points

The real time schedule always corresponds to the value of the available active power reduced by the amount of the positive FCR bid. The control reserve mode of the power plant cluster is activated about 30 seconds before the start of the FCR bid, so that the active power can follow the real time schedule just in time to fulfil the requirement for 100% availability of provided FCR (see *FCR_02* in Tab. 1). The control system reduces the active power generation by the amount of the positive FCR bid to be able to activate the positive control reserve. During the phase of the simulated frequency drop (rise), the power plant cluster receives the set point signal to power up (down) the active power by the amount of the positive (negative) FCR bid plus a safety factor. The activated FCR $av(t)$ in positive or negative direction is equivalent to the deviation of the active power from the real time schedule.

The mentioned safety factor is implemented in the VPP as an offset correction function and is necessary for two reasons. First, to avoid any underfulfillment because of fluctuations of the active power. Second to compensate a possibly inaccurate calculation of the AAP that has to be forecasted rollingly by the power plants themselves.

In the following subchapter, one exemplary evaluation of a control reserve field test with the developed KPIs is presented.

4.2 Application of KPIs to REstable Field Tests

In the following evaluations, the offset correction function of the VPP will be disregarded in order to get a clear comparison of the KPIs according to the old and the new requirements without any computational modification of time series. In this example, the power plant cluster receives a set point of 12.5 MW for positive FCR activation and 10.5 MW for negative FCR activation. Fig. 6 shows an extract of the FCR time series with the according different tolerance corridors. The old requirements apply in the left diagram and the new requirements in the right diagram.

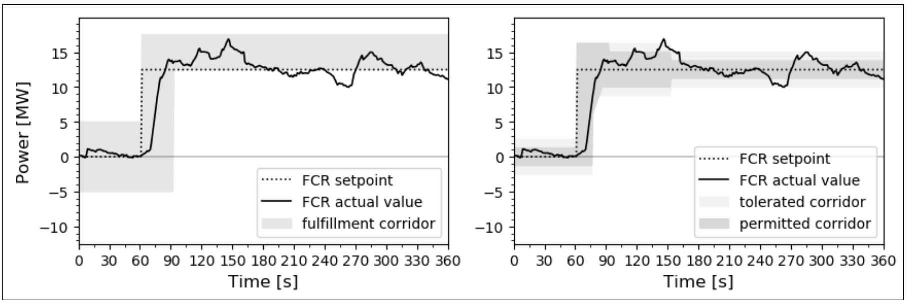

Fig. 6: Limits of fulfilment corridor (left) and limits of permitted and tolerated corridor (right)

One can see clearly the underfulfillment of the required FCR caused by an overestimation of the AAP (left diagram). The permitted and tolerated corridors for both positive and negative deviations of the FCR according to the new requirements (right diagram) lead to the result, that there is no underfulfillment in the illustrated extract.

The activation quality for the whole time slice of the test is presented in Fig. 7, separated into positive and negative FCR and times without FCR call. For the positive and negative FCR, the quality is better according to the new requirements, as they allow both over- and underfulfillment to a certain extent. This leads to an activation quality of 83.94 % according to the old requirements and 90.58 % for the new ones.

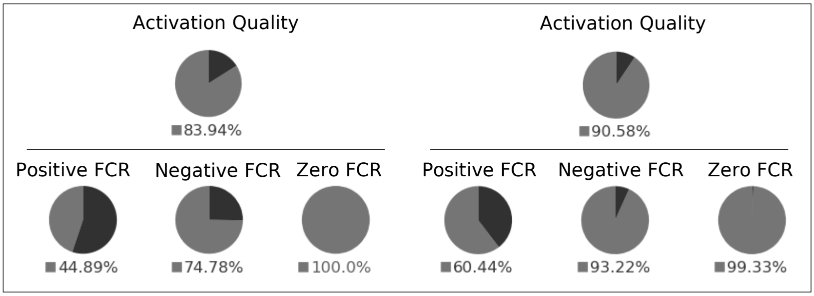

Fig. 7: Activation quality control reserve field test for old (left) and new requirements (right)

5 Discussion and Conclusion

The operated control reserve field tests as part of the REstable project are a success regarding the transnational established ITC infrastructure and the overcoming of regulative and technical obstacles for a centralized control of decentral European fluctuating power plants.

The developed KPIs allow a transparent verification of the fulfilment of control reserve requirements. A quantitative interpretation of the results regarding the activation quality is currently difficult as there are no comparable figures available. Moreover, the project did not claim to draw statistically relevant conclusions from the tests, because the number of tests was limited due to an agreed limited amount of energy losses. Nevertheless, some aspects could be detected which lead to loss of performance in the KPIs. First, a systematic overestimation of the calculated AAP can cause a merely arithmetical underfulfillment of the required FCR value. The offset correction of the VPP can compensate this theoretically, but it is not an officially proven procedure yet. Second, some general technical aspects can lead to slower reaction times of the power plants. For example, the interval for the acceptation of set point signals by the power plants has to be adjusted as short as possible, as current default values are up to 60 seconds to protect the power plants. Moreover, the communication chain in this system architecture from the central frequency emulator via the power target converter via the aggregator to the power plants can lead to latencies of a few seconds.

The further development of the technical requirements for control reserve seems to be more fitting to the control behaviour and the variability of renewable energies. According to the new requirements, a deviation from the set point is tolerated in both positive and negative direction and a distinction is made between a transient and a stationary area after each set point change. Moreover, the results of the field test show a better activation quality for the new requirements.

As a conclusion, it is possible to perform FCR of good quality with fluctuating energies aggregated transnationally within a VPP. A hundred percent fulfilment of the TSO's requirements on FCR is still not possible. Moreover, some regulations have to be amended to open the FCR market for fluctuating energies, such as the lengths of the bidding time slices and the lead times or the permission for control area crossing aggregation of power plants, for example.

Acknowledgments

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