Enhanced contribution of photovoltaic power systems to frequency control in future power systems

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Abstract
In contemporary grid infrastructure, grid frequency is still predominantly controlled by conventional power plants. However, the increasing installed power of distributed energy resources and the declining amount of synchronous generators will necessitate major participation of wind farms as well as photovoltaic systems in frequency control. From a technical point of view, PV inverters are able to provide not only manual but also automatic frequency restoration reserves as well as frequency containment reserves. However, market and regulatory conditions are not designed for them to participate yet. As power electronic-based systems, photovoltaic inverters are able to react even faster to frequency deviations than conventional power plants. This characteristic is leveraged to analyse the contribution of photovoltaic systems to stabilise the grid frequency. Therefore, a new control reserve product, called fast frequency containment reserves is developed. It is shown that the frequency stability can be considerably improved by integrating PV systems into frequency control.

1  |  MOTIVATION

Frequency control, a subcategory of general grid ancillary services, plays an important role in ensuring the stability of the power system. Today, grid frequency is predominantly controlled by conventional power plants with synchronous generators. Their mechanical and electrical characteristics ensure an inherent coupling of load balance and grid frequency by automatic provision of inertia in case of frequency deviations. In addition, the market-based products of control reserve are mainly supplied by synchronous generators as well.

The power system in Germany, however, has been changing significantly in past decades. More and more distributed energy resources (DER), especially wind farms and photovoltaic (PV) systems, have been integrated. In Germany, the share of renewable energy in the gross electricity consumption increased to 42.6% in 2019 and this trend is still persistent [1]. Today, during several hours of the year, the national load can already be almost completely covered by renewable energies, as seen on 1st May, 2018, with a share of 93.7% between 1 and 2 PM [2].

As Germany is set to pursue the goal of a prospective 100% renewable energy scenario, the number of synchronous generators will further decline. In order to reduce must-run units and to conserve the high security of supply, it is essential that wind farms as well as PV systems as future dominant power source will also be the major contributor to tasks of frequency control. With 60.87 GW of wind farms and 49.17 GW of PV by the end of 2019, these technologies are the ones with the highest installed power in Germany [3]. In this study, the contribution of PV systems to stabilise the grid frequency is analysed.

The provision of control reserve with wind farms has already been an intensively researched aspect for years. The research project TWENTIES has already shown that wind power plants can provide frequency restoration reserve from a technical point of view. A high degree of forecasting accuracy is required to avoid unnecessary curtailment [4]. The technical suitability for the provision of control reserve from renewable energies, including wind farms and PV systems, was also shown in the research project Kombikraftwerk 2 [5].

On this basis, the research project Regelenergie durch Windkraftanlagen investigated not only technical skills but also practical aspects such as the preparation of offers for the control energy market and verification procedures. The development of the method 'available active power', in which the system is curtailed in relation to the maximum possible feed-in instead of the schedule value, is essential for the provision of...
control reserve with fluctuating producers. The application of this approach avoids unnecessary curtailments and thus fundamentally increases the economic efficiency of providing control reserve [6].

These findings formed the basis for the pilot phase for wind farms to provide negative manual frequency restoration reserve in Germany, which started in January 2015 [7]. By November 2019, 80 MW had already been prequalified in this pilot phase [8].

Photovoltaics has so far played a minor role in research into the provision of control reserve. The fast controllability of PV inverters has already been proven in the literature [9, 10]. In the research project Regelenergie durch Wind- und Photovoltaikparks, wind farms and PV systems were combined to provide control reserve. The available active power of the PV systems was determined with the help of irradiation sensors or reference systems. While the former method does not provide sufficiently accurate results for the PV system used in this project, reference systems are much more suitable for determining the available active power. Disadvantages lie in the parameterization and individualization of the methods [11].

In the research project PV-Regel, an inverter-internal control system was developed to determine the available active power of PV systems while being curtailed with high accuracy. This method offers several advantages over the use of irradiation sensors and reference systems [12].

This control procedure forms the basis for the investigations on the frequency containment reserve (FCR) and other measures supporting the frequency carried out in this paper. Therefore, the behaviour of the inverter with implemented FCR statics is first tested in the laboratory and analysed in detail. In addition, a new control reserve product will be developed beyond the existing FCR to use the full technical possibilities and ensure frequency stability in a future inverter-dominated grid. The integration of this product is carried out in a balance model, which represents the grid with its components in an aggregated way. This allows to show the added value in terms of frequency stability. In contrast to [13], the new control reserve product is developed in order to substitute some part of the FCR, not to be an additional product that causes additional costs.

In this paper, only current-controlled PV inverters are considered. These are not able to react instantaneously to frequency deviations, so that a provision of inertia is excluded. Furthermore, an analysis of the frequency stability is presented without considering further aspects of the stability of an electric power supply system, such as voltage or rotor angle stability. Mutual interactions do occur at this point and have to be considered in further work, but are not subject of this paper.

2 Present Framework of Frequency Control

Today’s framework of frequency control measures considers PV systems only to a marginal extent. Technical requirements are solely defined for handling extreme frequency deviations. In general, PV inverters are designed to feed in as much active power as possible. They are usually controlled to convert the maximum available power to the PV generator, operating at its maximum power point (MPP). The MPP of the PV system is mainly dependent on solar radiation and temperature. Figure 1 shows the voltage–current and voltage–power characteristics to define the MPP.

The variable $I_{oc}$ represents the short-circuit current, whereas $V_{oc}$ states the open-circuit voltage. The parameters defining the MPP are the MPP current $I_{MP}$ and the MPP voltage $V_{MP}$.

Frequency control by inverters had generally not been considered until a few years ago, since PV had not been expected to be installed in such a significant proportion as it is today. Therefore, PV systems are currently only obliged to adjust their power output when severe system instabilities occur. While the first grid codes considering renewable energy in Germany required them to immediately disconnect from the grid at frequencies surpassing 50.2 Hz, a frequency-dependent active power reduction was implemented in 2012 for reasons of system stability in critical conditions. When the frequency is deviating 200 mHz above the rated frequency $f_0 = 50$ Hz, all DER must instantly start to reduce their current active power feed-in as a function of grid frequency in order to avoid a system collapse [14]. The corresponding function is shown in Figure 2.

This is currently the only technical requirement for PV systems concerning frequency control. In the normal operating state of the power system, where control reserve is applied in order to stabilize grid frequency, PV systems have not been involved yet.

One reason for this can be seen in the fact, that currently, the conditions of the control reserve market as well as the prequalification processes and further requirements from the transmission system operators (TSO) have historically mainly been based on the characteristics of synchronous generators. In Germany, the three control reserve products, (a) Frequency Containment Reserves (FCR), (b) automatic Frequency

![Figure 1: Characteristics of voltage and current as well as voltage and power of a PV system](image1)

![Figure 2: Frequency-dependent active power reduction](image2)
Inertia

30 s 5 min 15 min

FIGURE 3 Schematic illustration of frequency control measures

FIGURE 4 Required characteristic for FCR provision [16]

Restoration Reserves (aFRR), and (c) manual Frequency Restoration Reserves (mFRR), are procured via the online platform ‘regelleistung.net’. Figure 3 schematically depicts the chronological order of frequency control measures after the occurrence of a frequency deviation.

As soon as a frequency deviation higher than 10 mHz from the rated frequency occurs, FCR is activated. The grid frequency measurement is implemented at each individual provider of FCR and is therefore a decentralized measurement. The dead band of $f_0 \pm 10$ mHz results from the tolerated measurement inaccuracy of $\pm 10$ mHz. All providers in the Regional Group Continental Europe are activated at the same time. FCR is a proportional control and hence used to stop any drop or rise of the grid frequency. Present guidelines for FCR stipulate a steady rate of activation being completed within 30 s in case of a quasi-steady-state frequency deviation of $\pm 200$ mHz. FCR needs to be provided for at least 15 min, if required. This type of control reserve tides over the instantaneously acting inertia on the one hand and aFRR with an activation time of 5 min on the other hand. The required FCR characteristic is depicted in Figure 4 [16].

In contrast to FCR, the task of aFRR is to restore the frequency to 50 Hz, which requires a proportional-integral control. This type of control reserve has to be fully activated after five minutes and is gradually replaced by mFRR. These reserves are intended to support energy balances for long-term frequency deviations. The full activation of mFRR is completed 15 min after the incident and has to be provided for up to one hour.

The demand for control reserve providers to participate in weekly auctions, weekly or four-hour time slices, or using a ‘fixed generation schedule’ as a reference for the provision of control reserve are only some obstacles that prevent PV systems from participating in the control reserve market today [17]. Recent changes that were implemented in July 2018 by the German regulatory agency (Bundesnetzagentur), which are aiming at integrating especially fluctuating energies, slightly improve market conditions for PV. Time slices of aFRR sales are reduced to four hours and daily auctions for aFRR and mFRR are implemented, for example [18, 19]. Moreover, in 2015, the four German TSOs launched a pilot stage for wind farms to participate in the control reserve market for negative mFRR. During this pilot stage, the providers are authorized to reduce their active power in relation to their ‘available active power’ and not based on a ‘fixed generation schedule’ [7]. PV systems, however, are not included in this project. Therefore, taking part in the German control reserve market is not reasonable under today’s conditions.

3 | CONTROL RESERVE WITH PV SYSTEMS

In order to reach the goal of Germany’s government to provide 80 % of the gross electricity consumption with renewable energies in 2050 [20], the ability to provide control reserve with PV is essential. Although market conditions and regulatory frameworks prevent PV systems from participating in the market today, research has shown their technical ability to do so (cf. Section 3.1).

Different methods of how PV systems can provide control reserve are described in the first part of this section. Subsequently, the FCR function of a PV inverter prototype is specified. Finally, laboratory measurements show the application of this feature for specific frequency profiles.

3.1 | Verification procedures for control reserve delivery with PV inverters

The main challenge for PV inverters delivering control reserve is to determine the available active power while the inverter operates below its MPP. This curtailed operation mode is necessary for delivering negative and withholding positive control reserve. Any method developed for this can be classified into the two categories of passive and active verification procedures.

In the former, the available active power is calculated based on using one or more reference parameters. These may, for instance, include weather or power forecasts, data from pyranometers, or the power output from reference PV systems. In [21], a reference PV system was used to determine the available active power of another PV system being operated below its MPP. Results of a potential prequalification process shows that the requirements currently applied to wind farms in the above-mentioned pilot stage [7] can be easily met with PV systems.

Active verification procedures, in contrast, repeatedly adjust the present power output of the PV system for short periods of time in order to determine the potentially available maximum active power [21]. Figure 5 shows the functional layout of a
prototypical PV inverter with the ability to provide control reserve.

The power reserve controller is responsible for varying the operation point of the PV inverter such that the maximum available active power can be estimated at the same time. This function enables the system to be run at a defined operation point below the maximum available power. When receiving a request from the system operator (for aFRR or mFRR) or from decentralized frequency measurements (for FCR), the control reserve management specifies the required power reserve setpoint and passes it on to the power reserve controller. A steady and defined operation below the maximum available power is necessary for providing positive control reserve and can be achieved by using this inverter layout. While being operated below the MPP the voltage at one string is varied to determine the maximum DC power. At the same time, the second string compensates for the power fluctuations caused by the first string in order to keep the output power of the inverter constant at the set point. If control reserve is needed, this system can easily increase or decrease its output power by a predefined amount and thereby stabilize the power system [12, 22].

In [23], an inverter, equipped with this active verification method, was used in laboratory conditions to show the general ability of PV systems to provide control reserve. Figure 6 shows the stand-by and delivery process for 2 kW negative control reserve first and, in the second half of the day, delivery and stand-by for 3 kW positive control reserve. The setpoint is well observed with a high accuracy.

Both passive and active verification procedures are suitable for determining the maximum available power while withholding power reserves. The choice depends on the installed power, the homogeneity, shading effects, and the degradation of the PV system as well as the type of the installed inverters. In general, passive verification methods are more suitable for homogeneous PV systems with an installed peak power less than 1 MW. Active procedures are principally applicable to all types of systems, as they inherently take into account the plant characteristics. However, an evaluation should always be individual depending on the system [12]. In the following analyses, the described active verification method of the prototypical PV inverter is used.

3.2 Laboratory setup for frequency analyses

The ability of inverters to reduce their active power depending on the grid frequency is both needed for providing control reserve and for the frequency-dependent active power reduction in severe system instabilities (cf. Section 2). While the requirements for the latter define a steady gradient (see Figure 2), specifications for control reserve depend on the product (see Figure 3). Especially the delivery of FCR requires a high speed of active power adjustment. All FCR requirements are explained in detail in Section 2.

In order to demonstrate the functionality of the PV inverter in situations of under-frequency and over-frequency using the frequency-dependent active power reduction as well as its control reserve capability, a laboratory setup is established in the DER grid integration laboratory [24]. This setup consists of a grid simulator, the introduced three-phase PV inverter prototype and two identical DC sources. The nominal power of the grid simulator is 45 kVA and the prototypical inverter is rated at 20 kVA. The two DC sources have a rated power of 10 kVA each. An illustration of the laboratory setup can be found in Figure 7.

The grid simulator as a bidirectional voltage source is used to model the external grid. The PV inverter is connected to the
TABLE 1  Current–voltage characteristics used in the laboratory setup

| Current  | Voltage  |
|----------|----------|
| $I_{sc} = 15.6\, \text{A}$ | $V_{sc} = 812.5\, \text{V}$ |
| $I_{mp} = 14.8\, \text{A}$ | $V_{mp} = 650\, \text{V}$ |

DC sources that are configured with PV characteristics, as mentioned in Table 1, to represent PV generators (see Figure 1 for MPP and variable definition). The DC sources are operated with an irradiation density of 96%.

The setup records the grid frequency and the active power that is delivered by the inverter (AC). An average value is taken every 0.3 s for the frequency measurement and every 0.2 s for the active power.

3.3  Frequency-dependent control strategies of PV inverters

Although the frequency-dependent active power reduction at $\nu = 50.2\, \text{Hz}$ has been established with system security in mind only, it also provides a good overview of how fast a market-ready PV system reacts to frequency deviations. In order to evaluate the dynamic behaviour of the inverter, a step response of the frequency is measured. Figure 8 shows the response of this function of the PV inverter to a frequency step from 50 to 50.3 Hz.

The active power reacts to the frequency step with a gradient of 767 W or 0.04 pu, respectively, within 420 ms. The steady state of the active power of 17.4 kW is achieved within approximately 3 s. Taking the characteristics of the power electronics from PV inverters into consideration, the main advantage—when compared to conventional power plants—is the speed of control, resulting in fast adjustments of the active power. This behaviour is typical for inverters and not only shown by PV but also by battery inverters. This means that a provision of control reserve can be implemented not only for mFRR and aFRR but also for FCR—the product with the lowest activation time. The complete activation of a predefined power reserve can easily be achieved within 30 s. In [9] the provision of FCR was successfully tested under laboratory conditions. In those studies, a freely programmable inverter was used for FCR implementation instead of the prototypal PV inverter which is used in the setup for the analyses in this study.

The above-explained PV inverter prototype is additionally equipped with a specific function based on the requirements for FCR. All parameters of the FCR characteristic can be set as desired, i.e. dead band, frequency of full activation, gradients etc. In the following, the parameters are set as in the FCR characteristic curve shown (see Figure 4), including a dead band of $f_0 \pm 10\, \text{mHz}$ and a full activation of control reserve at a frequency deviation of $\pm 200\, \text{mHz}$. The active power reserve (APR) is set to $\pm 4\, \text{kW}$. The control actively adjusts the momentary power output of the inverter in order to provide control reserve. This function can be enabled and disabled as required.

First, the FCR response of the PV inverter with the implemented characteristic is shown in a under-frequency scenario. Afterwards the same setting is displayed for over-frequency. In both measurements the frequency-dependent active power reduction is deactivated. Finally, the response of the PV inverter in a combined consecutive over- and under-frequency situation is shown without FCR, but with frequency-dependent active power reduction activated. This last measurement shows the response of the PV inverter in safety-critical situations of the power grid. In the provision of FCR, the focus lies on the behaviour in the seconds range, the transient behaviour plays a minor role and is rather assigned to the inertia. In the following measurements, the FCR provision at frequency steps is examined, so that the stationary final value is decisive.

Figure 9 shows the measured results of the frequency steps in the under-frequency range applied by the grid simulator as well as the active power response of the prototypal inverter with activated FCR function. At 10 s the grid simulator sets a frequency of 49.9 Hz and at 20 s a frequency of 49.8 Hz. After 30 s, the frequency returns to its nominal value of 50 Hz.

As a situation of under-frequency requires additional active power to stabilise the frequency and the PV inverter operates with an activated FCR function, its output power increases when confronted with frequency dips. The required active power of 2 kW per 0.1 Hz is achieved with high accuracy.

Between 20 and 30 s, a slight fluctuation in the power output is visible in the measurement. This is caused by the inverter’s control during the provision of power reserve with the above-mentioned procedure (see Section 3.1). Especially at high power levels close to the nominal power of the inverter, the change of the two strings determining the MPP is visible as small leaps. Since these minor fluctuations occur only in very short...
periods of time and the mean value has negligible effects on the steady-state value, this behaviour is considered as acceptable for frequency stability.

The frequency steps of 0.1 Hz in the over-frequency range exactly reflect the tests in the under-frequency range. Every 10 s the frequency raises about 100 mHz. Figure 10 shows the measured frequency as well as the response of the PV inverter with activated FCR characteristic.

Immediately after the over-frequency deviations from the nominal frequency occur, the inverter reduces its active power by 2 kW per 0.1 Hz. This is exactly what the FCR characteristic requires.

The data presented shows that the FCR function of the inverter prototype can well fulfill its designated purpose. The APR of 4 kW at the maximum is adhered in each frequency step. A bidirectional delivery of positive and negative power reserve can be reached easily, if the inverter is able to operate below its MPP with high accuracy. From a technical point of view, the used FCR function in this inverter is a feasible way to provide this control reserve product. Furthermore, additional investigations concerning accuracy estimation of the performance of the inverter control for fFCR must be considered.

One challenge, however, is that the FCR characteristic of the PV inverter must be matched to the function of the frequency-dependent active power reduction. If the frequency of the grid exceeds 50.2 Hz, the safety-relevant frequency-dependent active power reduction needs to substitute the FCR characteristic. Once the frequency-dependent active power reduction has been activated and, as a result, the active power is reduced, the inverter is only allowed to return its active power to the previous value with a slow gradient [15], even if the frequency afterwards slides into under-frequency conditions afterwards. In serious incidents with large frequency gradients (e.g. in case of a system split), this performance can lead to severe problems. Although required by current grid regulations, this may pose an adverse behaviour to grid stability in situations of heavily fluctuating frequency.

In the first test, the coordination of these two characteristics was not necessary because the frequency did not exceed 50.2 Hz. In the next measurement the FCR function is deactivated in order to show the function of the frequency-dependent active power reduction. After 10 s, a frequency step from 50 Hz to 50.3 Hz is conducted. 10 s later, the frequency drops to 49.7 Hz. After another 20 s the frequency returns to the rated frequency of 50 Hz. This large frequency variation can realistically occur during serious system failures such as system split scenarios. The measured results of this test are shown in Figure 11.

As soon as $f > 50.2$ Hz the active power of the inverter fed into the grid is immediately reduced according to the requirements. The slight overshoot of the power at $t = 10$ s is caused by the high dynamics and the step response of the inverter’s control. After 20 s the effect of the slow active power adjustment according to the requirements from the frequency-dependent active power reduction can be seen. The maximum available active power is not achieved immediately after the under-frequency has occurred and as can be seen in Figure 9. The maximum gradient after such a critical frequency situation is 10%/min of the maximum power [25]. This behaviour entails that the recovery from the frequency-dependent active power reduction would prevent the inverter from supporting under-frequency situations with positive FCR if needed. In these cases, however, high dynamics are required for high frequency
stability. A solution for coordinating both functions still needs to be found. For further investigations in this paper, however, the focus lies on the FCR.

Due to the characteristics of inverters, PV systems as well as battery energy storage systems (BESS) are able to react to a frequency deviation even faster than the specifications of FCR are requesting. This advantage can serve to stabilize the frequency in a future system with a lower share of synchronous generators and therefore less inertia and a higher share of inverter-based technologies. Therefore, a new type of control reserve is introduced, called fast frequency containment reserves (fFCR). This type of control reserve is located in the time frame between FCR and inertia. The arising gap between inertia and FCR is supposed to be limited by the fFCR. Moreover, fFCR will help integrating inverter-coupled DER into frequency control mechanisms by gaining from their convenient characteristics compared to synchronous generators. In this paper, fFCR will be implemented as a new dimension of frequency control.

4 FAST FREQUENCY CONTAINMENT RESERVES

In this section, the value for the power system of introducing a new type of control reserve is analysed. In the course of this chapter, the thesis is presented that with partially faster provision of FCR, called fFCR, frequency stability can be guaranteed even with a lower accelerating time constant of the grid. This is done in three steps.

The first step (A) is the definition of a reference incident. The maximum instantaneous power deviation in the ENTSO-E Regional Group Continental Europe is determined to be ±3000 MW. This is defined as worst case scenario in the un-split power system and needs to be managed by the provision of FCR [16, 26]. The second step (B) consists of the product definition of fFCR: Based on the configuration of FCR and technical characteristics of PV inverters, an analysis of parameters is conducted by means of a simulation model. The results state the relevant parameters for defining fFCR. Step 3 (C) comprises the application of fFCR: Having specified the technical requirements for fFCR, the new combined reaction of fFCR and FCR to the reference incident is applied in the simulation model as well as in the laboratory. The impact of implementing the new product is illustrated. Results for this approach are detailed in the following paragraphs.

4.1 Reference incident

The above-mentioned reference incident and especially the power deviation of ±3000 MW are based on the simultaneous failure of the two biggest block-unit power stations within the Regional Group Continental Europe. In order to handle this loss of power generation, the same amount of power needs to available, so that the balance can be maintained. This is why ±3000 MW of FCR is provided in this area. In [27] a design hypothesis is developed, which outlines the dynamic and quasi-steady-state limits of frequency deviation in case of this reference incident:

- Maximum quasi-steady-state frequency deviation of 180 mHz when considering the self-regulating effect of the load or 200 mHz without including it, respectively;
- Maximum dynamic frequency deviation of 800 mHz.

The self-regulation effect of the load (SRE) is the intrinsic contribution of frequency dependent loads to frequency stability. It describes the percentage change of the active power in case of a frequency deviation. This occurs instantaneously and its form and intensity depend on the type of consumer [28]. The frequency response $f$ after the reference incident results from the sum of the rated frequency $f_0$ and the integration of the rate of change of frequency (RoCoF) $\dot{f}$ [29]:

$$f = f_0 + \int \dot{f} \, dt = f_0 + \int \frac{\Delta P}{P_{Gen}} \cdot \frac{f_0}{T_{Grid}} \, dt$$

(1)

$\Delta P$ is the power imbalance, $P_{Gen}$ is the actual power of the generation and $T_{Grid}$ is the accelerating time constant of the grid. $T_{Grid}$ specifies the inertia in the system and is calculated by Equation (2) [29].

$$T_{Grid} = 2H = \frac{\Omega_r^2}{P_{Gen}}$$

(2)

$H$ is the inertia constant, $\Omega_r$ is the rated angular velocity, $f$ is the moment of inertia and $P_{Gen}$ is the actual power of the generation. In steady state conditions the amount of power of the generation is assumed to be equal to that of the load. Thus, the accelerating time constant can be determined based on the
load instead of the generation. ΔP is composed of the incident power \( P_{Inc} \), the power of the self-regulating effect of the load \( P_{SRE} \), and the control reserve power \( P_{FCR} \):

\[
\Delta P = P_{Inc} + P_{SRE} + P_{FCR}
\]

(3)

\( P_{SRE} \) is calculated by the self-regulating effect of the load \( SRE \), the frequency deviation from the rated frequency and the grid load \( P_{Load} \):

\[
P_{SRE} = SRE \left( f_0 - f \right) P_{Load}
\]

(4)

\( P_{FCR} \) results from the current requirements which apply to the activation for FCR, including a dead band of \( f_0 \pm 10 \) mHz (see Table 2) [16]. Beyond the dead band, FCR is activated linearly until the maximum activated power is reached. The block diagram in Figure 12 shows the determination of \( P_{FCR} \).

In order to calculate \( P_{FCR} \), different parameters have to be considered. First, the frequency deviation between the rated and the present frequency is detected. If this deviation lies within the dead band, no further action is executed. Otherwise the FCR, which needs to be activated at this deviation, is calculated by the self-regulating effect of the load \( SRE \), the frequency deviation from the rated frequency and the grid load \( P_{Load} \):

\[
P_{FCR} = \frac{\text{Limit}}{49.0} \left( f_0 - f \right) P_{Load}
\]

FIGURE 12 Block diagram of calculating the control reserve power

The frequency stability analysis [31]. The reactions to frequency changes, such as intrinsic processes and the activation of control reserve, are also represented summarily in the system via the required behaviour. Thereby, the effects of fFCR on the existing power system and the reference incident can be shown. The values in Table 2 provide the basis for the following analyses and simulations.

These values are typical for the network of the Regional Group Continental Europe. In order to illustrate the design hypothesis, the load is assumed to be \( P_{Load} = 148 \) GW. This value represents a relatively low load and therefore demonstrates a worst-case scenario. Figure 13 shows the high consistency between design hypothesis (black line) and simulation model (blue line) after the reference incident at \( t_0 = 1 \) s. The application of this model for further studies is hence verified.

This reference incident was chosen in order to show the impact of fFCR in serious system instabilities. It thus represents a worst-case scenario and shows massive frequency disturbances as well as the effects of control reserve. Furthermore, the use of the reference incident offers the possibility to compare the results with other alternative measures. The effects can certainly be transferred to minor frequency deviations as well but is not quite as crucial in these situations. The simulation is limited to the correlation of active power feed-in and grid frequency. It only considers primary control (proportional) and is not provided with secondary control (proportional-integral), corresponding to aFRR.

FIGURE 13 Validation of the simulation model and the laboratory setup in comparison to the design hypothesis

### 4.2 Definition of fFCR

The goal of fFCR is to generate a type of control reserve that supports the system stability in case of a frequency deviation. It becomes even more important when the system’s inertia declines and inverter-coupled generation rises. By applying the simulation model, parameters of FCR are varied while holding all other parameters constant. In this way, appropriate requirements for an fFCR delivered by PV systems are defined. In the
sensitivity analysis, the FCR variables (a) dead band, (b) power, (c) frequency of full activation and (d) activation time are examined one after the other regarding their impact on the course of frequency after the reference incident.

Simulation results show a very slight influence of varying the dead band of \( f_0 \pm 10 \text{ mHz} \) (Figure 14).

While no dead band improves the dynamic as well as quasi-steady-state frequency deviation minimally, a larger dead band however causes the opposite. A larger dead band would lead \( f\text{FCR} \) to be a control reserve product of emergency, because it would only be activated at high frequency deviations, thus limiting its operational use. As no significant difference can be seen between the existing dead band and no dead band and the inaccuracy of frequency measurement has to be regarded as well, the dead band of \( f_0 \pm 10 \text{ mHz} \) will be kept for \( f\text{FCR} \).

The provided FCR is based on the reference incident of a maximum instantaneous power deviation of \( \pm 3000 \text{ MW} \). This leads to an amount of FCR in the Regional Group Continental Europe of \( \pm 3000 \text{ MW} \) which is needed to handle this worst case scenario—without taking a system split under consideration. Figure 15 shows a provision of 4000 MW FCR and 2000 MW FCR instead.

If the amount of FCR is increased, more power is brought into the system than was extracted before. This results in unintended oscillations of the frequency which does not increase the system stability. Less power leads to an exceeding of the dynamic as well as quasi-steady-state frequency limits. Therefore, the amount of FCR, or in combination with \( f\text{FCR} \) respectively, is supposed to stay at \( \pm 3000 \text{ MW} \).

The frequency of full activation, which is at \( f_0 \pm 200 \text{ mHz} \) translating to \( f = 49.8 \text{ Hz} \) in this reference incident, affects the quasi-steady-state frequency deviation marginally (Figure 16).

Whereas the dynamic frequency deviation is equal in comparison to the reference incident, the quasi-steady-state deviation is smaller at a lower frequency of full activation and vice versa. Due to the small impact and greater stress for the providing units, the frequency of full activation is kept at \( f_0 \pm 200 \text{ mHz} \) for \( f\text{FCR} \) as well.

The most important impact on system stability is achieved by varying the activation time which is 30 s for FCR (Figure 17). Reducing the activation time leads to considerably smaller dynamic frequency deviations after the reference incident. The maximum deviation is reached after a short period of time, e.g. approximately 5 s for an activation time of 5 s compared to about 19 s for the reference incident. This leads to a faster return to the quasi-steady-state deviation. The same effect can
TABLE 3  Design of FCR and fFCR

| Parameter               | FCR   | fFCR   |
|-------------------------|-------|--------|
| Dead band               | $f_0 \pm 10$ mHz | $f_0 \pm 10$ mHz |
| Total power             | ±3000 MW    | ±3000 MW    |
| Frequency of full activation | $f_0 \pm 200$ mHz | $f_0 \pm 200$ mHz |
| Activation time         | 30 s   | 1 s    |

be observed for all variations. As inverter-coupled DER, like PV systems and BESS, are able to adjust their power within less than 1 s (see Figure 8), but, at the same time, at least 100 ms are necessary to get one reliable frequency measurement [32], an activation time of 1 s for fFCR is chosen and will be easily achievable.

These parameter studies suggest a product design for fFCR as shown in Table 3, compared to the parameters of FCR.

The dead band and the frequency of full activation are the same for fFCR and for FCR. The total power of activated FCR and fFCR is supposed to be ±3000 MW in both cases. The activation time for FCR is 30 s while the activation time for fFCR is 1 s. As part of the primary control, fFCR must be able to be kept for 15 minutes, just like FCR. This means that the advertised fFCR runs in parallel with the FCR and not sequentially. This means that the fFCR can completely substitute the FCR in its effect. If the approach of implementing the fFCR and FCR in sequence were to be followed, higher trading activity would also result in higher trading costs.

The next step is the validation of the simulation results in the DER grid integration laboratory on a smaller scale. fFCR is implemented as defined above and the impact of using inverters in this context for frequency control will be presented.

4.3 Application of fFCR

In the previous paragraph, a configuration of fFCR has been developed. The specifications in Table 3 are applied in a laboratory environment in order to verify the effect of this new type of control reserve. Therefore, a laboratory setup is designed and compared to simulation results. Figure 18 shows this measurement setup.

The grid simulator is used as a power amplifier and controlled by a field programmable gate array (FPGA), which uses the control of a virtual synchronous generator [33]. The reference incident is realized by adding a three-phase RLC circuit that serves as a load. The frequency control for FCR and fFCR is implemented on a freely programmable rapid prototyping inverter system [34]. In comparison to the inverter prototype from the studies in Section 3, the rapid prototyping inverter system is used, since there is more freedom in the design of the FCR and fFCR control. Voltages and currents are measured for each phase at the bus bar; frequency and active power are calculated from these values. This setup represents a simplified method to show effects of frequency control on a very small laboratory scale, although they usually occur on transmission system scales. The simplification, however, is legitimate if only relations between active power control and frequency are considered. This is done by aggregating all the components of the transmission system on one bus bar and by assuming that the frequency of the transmission system is identical throughout the whole network. Figure 14 shows the conformity of the design hypotheses (black line), simulation results (blue line) and laboratory setup (orange line) and thus validates the setup.

In Germany, PV systems have not participated in the control reserve market by now. BESS, however, are represented in the FCR market with a large amount of prequalified power. In November 2019, about 380 MW of BESS were prequalified [8], which represents a share of 66% of the German FCR demand of 573 MW [35]. Two thirds of FCR can thus already be replaced by fFCR provided by BESS inverters today. The impact of substituting only 1000 MW FCR by 1000 MW fFCR is shown in the simulation model as well as in laboratory measurements in Figure 19.

Results show that especially the dynamic frequency deviation is clearly smaller with the combined use of fFCR and FCR than in the reference scenario with FCR only. The limit of 49.2 Hz is not even reached with a maximum deviation of 49.45 Hz. Also, the quasi-steady-state deviation is reached earlier than in the reference scenario and therefore leads to higher system stability.
5 | INTRODUCTION OF FFCR IN GERMANY

As the support of the system’s frequency in case of severe incidents by using fFCR in addition to FCR has been shown to be advantageous, market conditions and regulatory frameworks need to be adjusted. Not only BESS but also PV systems need to be able to meet the underlying requirements for providing control reserve. Revisions from the Bundesnetzagentur as well as the four German TSOs have not been sufficient for PV systems to participate in the control reserve markets so far.

First of all, the verification method of a fixed generation schedule is not convenient for the delivery of control reserve with PV systems. Since they do not generate power dependent on the load but on solar irradiation, they usually feed in as much power as possible. Therefore, a curtailment based on the available active power is technologically adequate and feasible. Research has shown that suitable methods with a high precision exist. PV systems in general are qualified to provide negative control reserve very easily, while the provision of positive control reserve involves a consistent curtailment of the system. The potential for technical realization is given, but the profitability needs to be incentivized.

Furthermore, time slices of 24 h, as FCR is demanding at present, or 4-h time slices which is supposed to be implemented from July 2020 on, is not sufficient for PV systems to deliver a noticeable part of fFCR [36]. The potential of PV systems regarding control reserve is much higher if time slices are not longer than one hour because fluctuations can be predicted more accurately with short-time forecasts. In addition, it is important that tenders can be submitted in a short period of time before provision, i.e. not more than one day before. Otherwise the potential of provided power by PV systems would be severely limited because of safety margins in order to avoid contractual penalties.

All in all, PV systems are able to deliver fFCR from a technical point of view. However, additional studies are necessary to evaluate the system behavior of the fFCR supply of PV systems. More extensive statistical studies are also useful at this point in order to quantify the deviation in the provision of fFCR. From an economic perspective, there are two further aspects to be discussed. First, the financial incentive to provide fFCR and second, the barriers to market entry itself. Financial incentives can result from the quite large diversity factor of PV. In times of a surplus of energy from PV systems, market-based prices fall. If this leads to lower prices, even a slightly higher compensation is sufficient to create a financial incentive for the fFCR. The market barriers, on the other hand, are rather moderate if regulatory adjustments can be implemented. Adjustments only need to be done for creating appropriate conditions for PV to enter a potential fFCR market.

6 | CONCLUSION

With the change of the German electrical power system from mainly conventional generation with central power plants, driven by synchronous generators, towards a more and more decentralized generation with inverter-coupled technologies, the tasks of frequency control need to be reallocated. The minimisation of must-run units requires especially wind farms and PV systems to provide control reserve.

Although market and regulatory conditions currently prevent PV systems from taking part in the control reserve markets, they are able to deliver it from a technical point of view. Passive and active verification procedures serve as methods to overcome challenges of determining the available power while operating below the maximum power point. As the power output of PV inverters can be adjusted very quickly, they are able to deliver not only mFRR, but also aFRR and FCR. The FCR characteristic from the prototypical PV inverter, which is demonstrated in

![FIGURE 20 Activated control reserve of the reference scenario compared to the combination of FCR and fFCR](image-url)
this study, meets the requirements for FCR provision. When operating in a defined power reserve below the maximum power point, a symmetrical provision of FCR is possible. In situations of frequencies $f > 50.2$ Hz, when the frequency-dependent active power reduction sets in for system security, a coordination between both functions still needs to be worked out. In case of very high frequency gradients switching from over-frequency to under-frequency (e.g. in system split scenarios), the high dynamics of FCR provision would be overlaid by the slow recovery of active power after the activated frequency-dependent active power reduction. This may lead to severe problems when FCR is needed by these systems in such a scenario.

As even a faster reaction to frequency deviations than requested for FCR is possible with PV inverters, it has been demonstrated that they are not only able to provide FCR, but may also deliver faster FCR than conventional power plants. Regarding the decreasing amount of inertia in Germany, a new control reserve product, lying in the time frame between FCR and inertia is reasonable. This product is called fast frequency containment reserves (fFCR). Its goal is to stabilize the frequency in future power systems when less synchronous generators and more inverters are connected to the grid. Further investigations need to deal with the accuracy of providing this type of control reserve.

The implementation of fFCR is analysed in three steps. First, the reference incident with a maximum power deviation of ±3000 MW in the Regional Group Continental Europe is defined. This provides the basis for system stability studies where dynamic and quasi-steady-state frequency deviations are examined for different parameter configurations. A simulation model is developed in order to define the parameters for fFCR. Keeping all other variables constant, the parameters (a) dead band, (b) amount of FCR, (c) frequency of full activation, and (d) activation time are varied. Whereas results show that the influences of dead band, amount of FCR and frequency of full activation are either neglectable or not beneficial for technical or economic reasons, the activation time has a great impact on the system stability. The parameter studies lead to a definition of fFCR with an activation time of 1 s and a total amount of fFCR and FCR of ±3000 MW in the Regional Group Continental Europe. The verification of this new product is accomplished by setting up laboratory measurements on a small-scale level. Substituting one third of FCR by fFCR leads to a considerably higher system stability than the reference incident shows for today. The reason is that more power is provided in the first seconds after the incident. Analyses concerning the demand of fFCR still need to be conducted in further work. In these examinations, different possibilities of stabilizing the grid frequency, e.g. the provision of inertia from inverters, must be regarded. An optimal solution will probably involve a combination of different frequency stabilizing measures.

In order to introduce this new control reserve product fFCR into the power system, market and regulatory conditions need to be revised. If the appropriate framework is created, inverters are able to provide fFCR and, in this way, to contribute to higher system stability.
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