Dynamic monitoring of Frequency Containment Reserve activation

Philipp Maucher and Hendrik Lens

Kurzfassung

Dynamische Überwachung der Aktivierung der Primärregelleistung

Frequency Containment Reserve (FCR), auch bekannt als Primärregelleistung, ist die schnellste Art der Regelleistung (RL), die zur Frequenzhaltung eingesetzt wird. In der Vergangenheit wurde die FCR durch eine geringe Anzahl an großen Kraftwerken erbracht. Die technischen Anforderungen an die FCR-Aktivierung konnten daher manuell überprüft werden. Da die FCR zunehmend von einer großen Anzahl an kleineren Einheiten bereitgestellt wird, sind manuelle Verfahren in Zukunft keine praktikable Option. Aus diesem Grund wird in diesem Artikel ein Konzept für ein automatisiertes Monitoring der FCR-Erbringungsqualität im Betrieb vorgestellt.

Bevor jedoch das FCR-Monitoring durchgeführt werden kann, muss die gemessene Wirkleistung auf die Fahrplanleistung und die verschiedenen RL-Produkte aufgeteilt werden, da diese gleichzeitig bereitgestellt werden können. Dieser Artikel präsentiert eine Methode zur Trennung verschiedener RL-Produkte basierend auf dynamischen Modellen.

Im vorgeschlagenen Monitoringkonzept wird basierend auf dem FCR-Sollwert ein Toleranzkanal gebildet, der den zulässigen Bereich für die FCR-Aktivierung definiert. Dieser Toleranzkanal wird mittels eines dynamischen Modells festgelegt, das dem langsamsten Regelleistungserbringer entspricht, dessen FCR-Aktivierung noch als konform gilt.

Zur Auswertung von längeren Zeiträumen wird die tatsächliche FCR-Aktivierung relativ zum Toleranzkanal normiert. Abschließend werden die mit dem vorgeschlagenen Monitoringkonzept erhaltenen Ergebnisse für verschiedene Arten nicht-konformer FCR-Aktivierung, wie z.B. begrenzte oder verspätete Erbringung, diskutiert. l

Authors

Philipp Maucher, M.Sc.
Research Scientist

Prof. Dr.-Ing. Hendrik Lens
Head of Department Power Generation and Automatic Control
University of Stuttgart – IFK
Stuttgart, Germany

Frequency Containment Reserve (FCR), also known as primary control reserve, is the fastest active power reserve (APR) used for system balancing. In the past, FCR was provided by a limited number of large units and the technical requirements on FCR activation could be monitored by a manual procedure. Due to the fact that FCR increasingly is provided by a large number of smaller units, manual procedures are no viable option for the future. For this reason, this article describes an automated concept for monitoring the quality of the activation of FCR during operation.

Before FCR monitoring can be carried out, however, the measured active power has to be apportioned among the scheduled power and the different APR products, as they may be provided simultaneously. This article presents a method for the separation of different APR products based on dynamic models.

In the proposed monitoring concept, a tolerance channel is created based on the FCR setpoint, defining the admissible range for FCR activation. This tolerance channel is established by means of a dynamic model corresponding to the slowest reserve provider (RP) whose FCR activation is still considered to be compliant.

For the purpose of evaluation for longer time periods, the actual FCR activation is normalized relative to the tolerance channel. Finally, the article discusses results obtained with the proposed monitoring concept for different kinds of non-compliant FCR activation such as limited or delayed activation.

1 Introduction

1.1 Motivation

In a power system, production and consumption must always be in balance. If the planned production and consumption are not balanced, the difference is compensated by the synchronous generators of the power plants, leading to their deceleration (consumption > production) or acceleration (consumption < production) and, thus, to an according change of the system frequency. Since the admissible range for the grid frequency is limited, active power reserve (APR) must be used for stabilization. Frequency Containment Reserve (FCR) is used as the fastest kind of APR, which mitigates frequency changes quickly by activating active power proportional to the grid frequency.

In Europe, FCR is procured by Transmission System Operators (TSO) as an APR product, mostly on dedicated markets. In order to guarantee secure grid operation, the TSO drafted the definition of technical criteria for FCR in the EU network codes and their national implementations, among which minimum requirements on response times, dynamic behaviour, accuracy, and reliability. APR providers may offer FCR by means of generation units, storage devices, or loads (reserve providing units) or in groups of several units (reserve providing groups). In this article, both reserve providing units and groups are denoted as reserve providers (RP). To this end, before a RP can participate in FCR provision, its compliance with the criteria above is verified in a so-called prequalification procedure defined by the TSO. While this procedure may be repeated after some time (usually several years), it is not suitable to monitor whether the criteria are met during operation. Such monitoring, however, is a relevant contribution to creating a level playing field for the FCR market, as it prevents APR providers being paid for a service that actually is not provided at the quality required.

1.2 State of the art

In the past, FCR was provided by a limited number of large RP. Under such conditions, it was feasible to perform manual monitoring of FCR activation, meaning that the response of RP after relevant frequency events was analysed by experts of the relevant TSO based on ex-post data. However, due to the increasing provision of FCR by dispersed RP, manual monitoring is no longer practicable in the future. This is not only because of the sheer number of RP, but also because of the large variety of technologies that may behave quite differently depending on the mode of operation. This means that, for some technologies, the behaviour observed in the prequalification process demonstrates that the RP is capable to meet the criteria in principle, but not necessarily that it always does so during normal operation. As a consequence, an automated monitoring concept for FCR is needed.

The relevant technical requirements for the activation of FCR in Europe are defined in §154(7) of the SO-GL [1]:

"In case of a frequency deviation equal to or larger than 200 mHz, ...

1. at least 50 % / 100 % of the full FCR capacity shall be delivered at the latest after 15 / 30 seconds."
2. the activation of the full FCR capacity shall rise at least linearly from 15 to 30 seconds."

"In case of a frequency deviation smaller than 200 mHz, the related activated FCR capacity shall be at least proportional with the same time behaviour referred to 1. and 2."

The FCR activation shall also not be artificially delayed.

In order to understand the difference between prequalification procedures and FCR in normal operation, it is important to note that the SO-GL specifies the required FCR activation exclusively for a frequency step. This is reflected in prequalification procedures for FCR providers, e.g. of German TSO [2]: The compliance of a RP with the SO-GL is checked by means of FCR set-point steps (corresponding to frequency steps) with a large time interval of 15 min in between. Consequently, steady state is achieved between these steps. Hence, each of the steps can be considered as independent, allowing for direct application of the SO-GL. However, for the case of normal operation, during which the frequency is constantly changing, the SO-GL requirements must be adequately transferred to the case of a constantly changing frequency.

Compared to prequalification requirements, the automatic monitoring of FCR activation has not received much attention yet. Only a few methods have been published so far, and all of them have limitations, in particular with respect to the monitoring of dynamic performance. The German TSOs presented a monitoring concept that defines a tolerance channel by applying the SO-GL requirements directly on the measured frequency [3]. However, rapid changes in the frequency lead to undesirable behaviour of that tolerance channel. In France, the FCR activation during operation is checked based on several criteria. On the one hand, an admissible range is defined for frequency events (rapid frequency changes or large frequency deviations) using a first order transfer function. On the other hand, the offered FCR gain is compared with the actual FCR gain during operation for a longer time period [4]. In some interconnections of the United States, the response of individual governors is examined in order to assess primary frequency response (PFR), which is the APR that corresponds to FCR in Europe. However, this procedure is not feasible for a large number of RP. In the ERCOT grid, PFR is monitored using the ratio of the activated and the expected PFR in different time intervals (initial and sustained) [5].

The methods mentioned above either do not check the PFR activation automatically, not all dynamic aspects, or only based on rare events. Thus, they are not well suited for the task mentioned. Hence, a new monitoring method is required that is able to evaluate the quality of the stationary and dynamic FCR activation continuously and automatically for a large number of RP in real operation.

Apart from the monitoring as such, a further challenge is given by the fact that RP can provide several APR products simultaneously. However, only one quantity is measurable: the active power fed into the grid. As a consequence, there is a need to apportion this single value to the different kinds of APR provided. An appropriate separation of the different kinds of APR is not a trivial task. We provide a procedure for the separation that is advantageous compared to existing ones.

2 Separation of different APR products

In order to be able to monitor different kinds of APR products, the actual power output related to the respective product is needed as an input, but only the entire power output of a RP is measurable. While the EU network codes define requirements for each single kind of APR, no procedure is specified that is to be used in order to determine the power output related to each APR based on the total power output of a RP. In fact, this is trivial during prequalification procedures, as then only the set-point of the APR product under consideration changes while all other components of the power set-point remain constant. Obviously, this assumption is not valid during normal operation. For this reason, this section provides a method for apportioning the total measured power output among scheduled power, FCR, automatic Frequency Restoration Reserve (aFRR), and manual Frequency Restoration Reserve (mFRR) [6], the latter two being further APR products (also known as secondary and tertiary control reserve) that are not in the main focus of this article.

2.1 Status quo and basic idea

The aim of the method is to enable the TSO to apportion the total power output in order to avoid further effort for the APR provider and to ensure equal treatment of all APR providers and technologies. If the APR providers were to assign the total power output, the TSO could not test their procedures for correctness and reliability. Therefore, only the following data which the APR provider transmits to the TSO is available for the separation of scheduled power, FCR, aFRR, and mFRR:

- total power output $P_{act,total}$,
- scheduled power $P_{sched,set}$,
- FCR set-point $P_{FCR,set}$,
- aFRR set-point $P_{aFRR,set}$,
- mFRR set-point $P_{mFRR,set}$.

In Germany, currently the entire deviation of the provision of APR is assigned to one product (aFRR; if no aFRR is offered: FCR; if neither aFRR nor FCR are offered: mFRR) [2]. In another approach, the deviation in the provision of APR is distributed proportionally to the products, depending on tolerance permitted for the respective products [3]. Both methods have the disadvantage that they assign the deviation of the provision of APR regardless of the activation dynamics. In both approaches, a very small FCR offer and a simultaneously large aFRR offer cause the FCR to hardly have any influence on the monitoring so that a lack of FCR activation cannot be identified.

The separation of the total power output is carried out on the basis of the transmitted data under the assumption that the activation of each of the products can be described by an appropriate model. These models are used to estimate the activated power of each product as a result of the corresponding set-point. For the sake of validation, the sum of all model outputs then is expected to yield the measured power output, even dynamically.

The structure of the overall model is shown in Figure 1. The actual activation for each of the various products is estimated from the corresponding set-point using a dynamic model of the respective activation so that the sum of all estimated actual activations corresponds to the estimated total power output $P_{act,total,est}$. Data from time periods in which only one of the inputs is excited (for example, FCR without a change in scheduled power, aFRR, and mFRR activation) can be used to estimate the corresponding dynamics with system identification techniques. Then, these estimated dynamics can be used to identify the dynamics of a second input, and so forth. The basic assumption that allows doing this is that the dynamics of the reaction to different power set-points can be superimposed.

In addition, an offset P_{offset} will be determined to take systematic deviations into

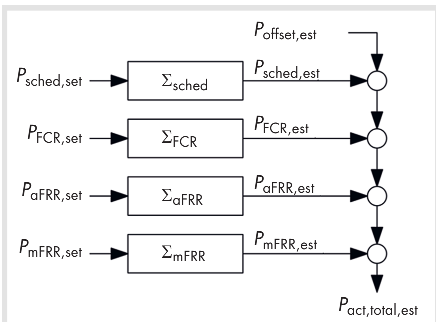

Fig. 1. Activation model-based separation of APR products.

account. This offset is assumed to be constant during a period with constant scheduled power and mFRR activation. Note that this procedure does not aim at modelling the provision of APR with high accuracy. Rather, the models are used as a pre-processing step for the monitoring of APR.

2.2 Identification of the activation models

In order to identify the activation models, time periods are determined in which the set-points of those models that have not yet been identified are constant. Since the FCR set-point changes continuously, the activation model for this product is determined first.

First, time periods are identified in which the activation of the other products is constant. Apart from any set-point changes, the time interval containing the subsequent activation has to be excluded as well. This is done based on the activation time (aFRR: 400 s (activation time of 300s plus security margin of 100s); mFRR: 900 s; scheduled power: 150 s from the end of the ramped set-point change; in the case of a set-point step, the ramping is estimated).

In order to obtain sufficient data for system identification of the identified time periods, only those with a length of at least 300 s are used. Assume that there are several such time periods T_k, where k is an index. For the actual FCR output $P_{k,\mathrm{FCR,calc}}$, it is assumed that the other products correspond exactly to their set-points. For systematic deviations, an offset $P_{k,\mathrm{offset}}$ is also determined in each time period.

The estimated FCR output $P_{k,\mathrm{FCR,est}}$ is calculated from the FCR set-point $P_{k,\mathrm{FCR,set}}$ using a second-order transfer function $G_{k,\mathrm{FCR}}(s)$. For each period k, $P_{k,\mathrm{offset}}$ and $G_{k,\mathrm{FCR}}(s)$ are optimized so that the quadratic error $\sum_{t\in T_k}|P_{k,\mathrm{FCR,est}}(t) - P_{k,\mathrm{FCR,calc}}(t)|^2$ is minimized. The final transfer function $G_{\mathrm{FCR}}(s)$ is the one from all periods k which has the median gain. This transfer function represents the activation model Σ_{FCR} for the RP under consideration. It enables the estimated FCR activation to be determined over the entire time period.

For the actual aFRR output $P_{\mathrm{aFRR,calc}}$, the activation model is determined for the whole period under consideration, because this achieves better results for real data than the determination of an activation model for every period without a change in scheduled power and mFRR activation. It is assumed that the scheduled power and the mFRR activation correspond exactly to their set-points and the FCR activation to $P_{\mathrm{FCR,est}}$. The offset is assumed to be the average offset of all FCR periods, i.e. for all T_k.

The activation model for aFRR, Σ_{aFRR}, consists of a rate limit $\dot{P}_{\mathrm{aFRR,ratelimit}}$ and a second-order transfer function $G_{\mathrm{aFRR}}(s)$. Their parameters are chosen such that the quadratic error $\sum|P_{\mathrm{aFRR,est}}(t) - P_{\mathrm{aFRR,calc}}(t)|^2$ is minimized.

As already mentioned in Section , the offset between two changes in scheduled power or in mFRR activation is assumed to be constant. The time periods T_l for determining the offset are those without a change in both scheduled power and mFRR activation. For the actual offset $P_{l,\mathrm{offset,calc}}$, it is assumed that the scheduled power and the mFRR activation correspond exactly to their set-points and the FCR and aFRR activation to $P_{\mathrm{FCR,est}}$ and $P_{\mathrm{FRR,est}}$, respectively.

The offset for each period is then calculated using the mean value of $P_{l,\mathrm{offset,calc}}$. For the offset during the changes (scheduled power or mFRR), it is assumed that this offset changes with a ramp from the offset of the previous period to the offset of the following period. The estimated offset $P_{\mathrm{offset,est}}(t)$ is thus determined for every point in time.

The time periods T_i for determining the scheduled power are those with a change in scheduled power. For the actual “activation” of scheduled power $P_{i,\mathrm{sched,calc}}$, it is assumed that the mFRR activation corresponds exactly to its set-point, the FCR and aFRR activation to $P_{\mathrm{FCR,est}}$ and $P_{\mathrm{aFRR,est}}$, and the offset to $P_{\mathrm{offset,est}}$.

The “activation” of scheduled power $P_{i,\mathrm{sched,est}}$ is calculated from the scheduled power $P_{i,\mathrm{sched,set}}$ using a rate limitation $\dot{P}_{i,\mathrm{sched,ratelimit}}$ and a first-order transfer function $G_{i,\mathrm{sched}}(s)$. For each period T_i, $\dot{P}_{i,\mathrm{sched,ratelimit}}$ and $G_{i,\mathrm{sched}}(s)$ are, again, chosen so that the quadratic error $\sum_{t\in T_i}|P_{i,\mathrm{sched,est}}(t) - P_{i,\mathrm{sched,calc}(t)}|^2$ becomes minimal. The model with the median rate limitation over all models is selected to estimate the “activation” of the scheduled power. This dynamic model enables the operating point $P_{\mathrm{operating}}$ to be determined over the entire time period.

The dynamic model for mFRR activation $P_{\mathrm{mFRR,est}}$ is determined in the same way as the estimated aFRR activation $P_{\mathrm{mFRR,est}}$, except that a first-order transfer function is used and that $P_{\mathrm{aFRR,est}}$, P_{offset}, and $P_{\mathrm{operating}}$ are used for the calculation of $P_{\mathrm{mFRR,calc}}$.

A subsequent update of the calculation of the dynamic model for aFRR activation is then possible to improve the results. For this update, all calculated results are used to calculate $P_{\mathrm{aFRR,calc}}$ instead of assuming that the activation follows the set-point directly. Otherwise, the procedure remains the same.

2.3 Distribution of the deviations to the products

We now have determined all dynamic activation models shown in Figure 1. However, the addition of all estimated product activations, $P_{\mathrm{act,total,est}}$, does not correspond to the total power output $P_{\mathrm{act,total}}$, since the model shown in Figure 1 cannot model noise. Moreover, the assumption that the dynamic response is identical over the entire period is also not completely fulfilled.

Therefore, the deviations have to be assigned to the APR products FCR, aFRR, and mFRR.

The total deviation is calculated as

$$P_{\mathrm{dev}}(t) = P_{\mathrm{act,total}}(t) - P_{\mathrm{act,total,est}}(t). \quad (1)$$

The chosen methodology apportions P_{dev} according to the offered FCR $P_{\mathrm{FCR,tot}}$, aFRR $P_{\mathrm{aFRR,tot}}$, mFRR $P_{\mathrm{mFRR,tot}}$, and the total offered APR

$$P_{\mathrm{APR,tot}} = P_{\mathrm{FCR,tot}} + P_{\mathrm{aFRR,tot}} + P_{\mathrm{mFRR,tot}}. \quad (2)$$

Consider the following example for the final aFRR activation $P_{\mathrm{aFRR,act}}$:

$$P_{\mathrm{aFRR,act}}(t) = P_{\mathrm{aFRR,est}}(t) + P_{\mathrm{dev}}(t)\cdot\frac{P_{\mathrm{aFRR,tot}}}{P_{\mathrm{APR,tot}}} \quad (3)$$

These quantities then can be used as input values for the monitoring procedure (which is described for FCR in Section 3). The results for aFRR can be compared with the separation method currently used by German TSO [2]. For this reason, the results of both methods are compared in Figure 2. The current method assumes that all products, except aFRR, are activated instantaneously and exactly. Hence, all deviations, especially changes of the set-point due to the schedule of the plant, are fully assigned to aFRR. As a consequence, this method causes large deviations in what is considered as actual aFRR provision during changes in other products, pos-

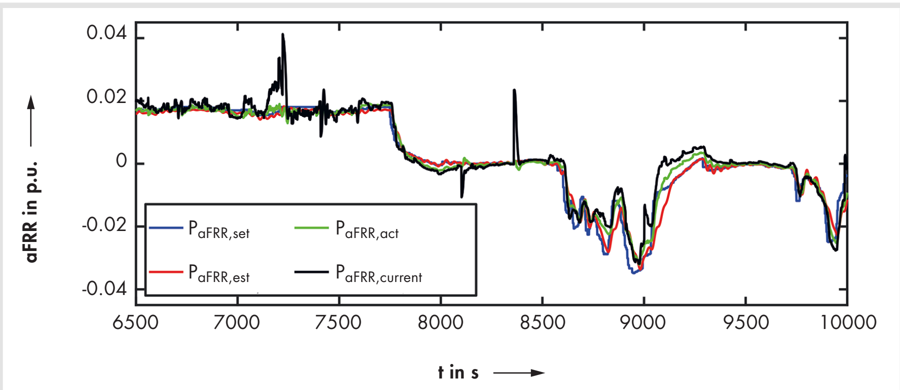

Fig. 2. Estimated (est) and final (act) output of aFRR and current method for separation.

sibly leading to unjustified cases of non-compliance detection. For example, consider the black line at about 7100 seconds. As the green line shows, the proposed methodology provides much smoother results such that non-compliance detection becomes more reliable and less challengeable. This is because the proposed methodology takes the dynamics of the activation of other APR products and of schedule changes into account.

3 FCR monitoring

This section presents a monitoring concept for FCR provision during operation which was originally presented in [7]. In the developed concept, dynamic tolerance channels are defined on the basis of the frequency. The evaluation of the compliance with the tolerance channel is performed using normalization. The monitoring concept therefore is called "Dynamic Normalization Methodology" (DNM). Section explains the initial situation for FCR monitoring. In Sections 3.2 to 3.4, the tolerance channel formation and the implementation of minimum tolerance channel widths are presented. Section 3.5 presents the evaluation of the tolerance channel results for a longer time period. Finally, the results for different non-compliant FCR activations are shown in Section 3.6. In this section, power is stated in p.u. with the offered FCR being the base value.

3.1 Initial situation

Figure 3a shows an FCR set-point curve resulting from a real frequency measurement (blue). The figure also shows the corresponding FCR activation by a generic pumped storage power plant model (black).

In this context, it is assumed that the FCR activation has already been separated from the schedule of the RP and from possible other types of APR according to the procedure described in Section . As already discussed, due to the fact that the frequency changes continuously, it is not straightforward to apply the criteria of the regulatory framework mentioned in Section , in order to determine whether the observed FCR activation is compliant. In contrast to a full activation time for a step-change, frequency-dependent tolerance channels that correspond to the admissible range of actual FCR activation could be used for arbitrary frequency signals. To this end, the following subsections present a method for defining such tolerance channels.

3.2 Tolerance channel

In the proposed method, a distinction is made between two different bounds for FCR activation: an upper and a lower bound. The bounds can be considered as "fast" or "slow", depending on the direction (positive or negative) of the change of the

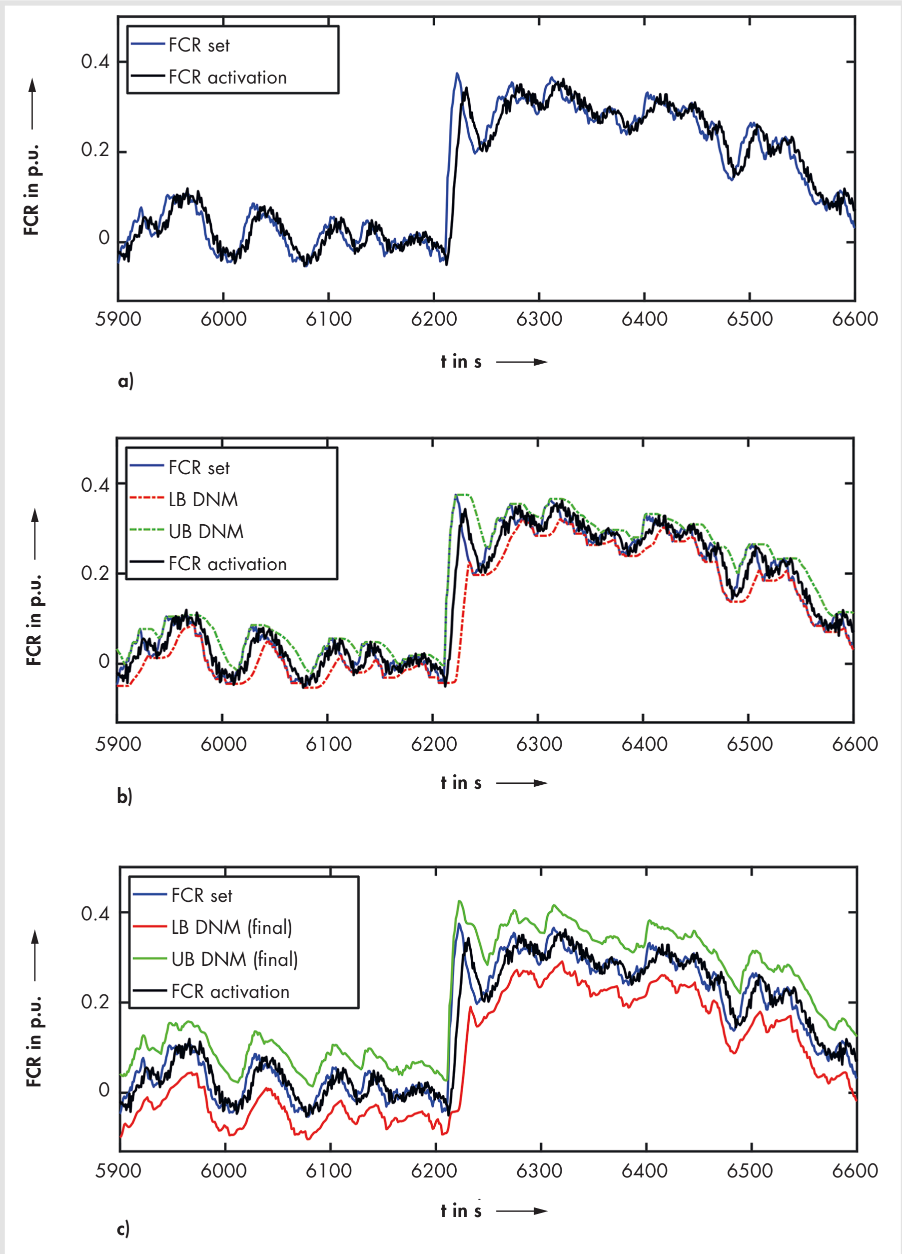

Fig. 3. a) FCR set-point and FCR activation.
b) FCR set-point, FCR activation, and tolerance channel without minimum tolerance channel width.
c) FCR set-point, FCR activation, and final tolerance channel.

FCR set-point. The procedure for a positive FCR set-point change is described below. In this case, the upper bound follows the set-point without delay and, thus, corresponds to the fast bound. For the lower bound, the FCR set-point is delayed by a dynamical system Σ (slow bound). The slow bound grants the RP adequate time to activate the requested reserve power. In the case of a negative FCR set-point change, the relationship is reversed: the lower bound then becomes the fast bound and the upper bound corresponds to the slow bound.

The definition of a dynamical system is needed in order to generalize the requirements, which are defined in the SO-GL for a frequency step only, to arbitrary frequency signals. The underlying assumption of choosing a *linear* dynamical system is that the FCR activation of the RP behaves as a linear system, which is approximately true in particular for slower technologies such as thermal power plants. However, the definition of the requirements in the SO-GL does not correspond to the step response of any linear system. For that reason, we propose the following linear system of third order with an output time delay T_d=10 s:

$$\Sigma: \begin{cases} \dot{x}(t) = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -0.04 & -0.4 & -0.75 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0 \\ 0.04 \end{bmatrix} u(t) \\ y(t) = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} x(t - T_d) \end{cases} \tag{4}$$

$$x = [P_{out} \ \dot{P}_{out} \ \ddot{P}_{out}]^T \tag{5}$$

$$u = P_{FCR,set} \tag{6}$$

$$y = P_{out} \tag{7}$$

Figure 4 shows the minimum requirements (black) according to SO-GL and the slower bound $P_{SB} = P_{out}$ defined by (4) to (7) (red) for a positive FCR set-point step (blue). That slower bound corresponds to the lower bound for FCR activation. As Figure 4 shows, the step response of this system is an approximation of the SO-GL requirements. In particular, it is less strict for $t > 15$ s, in order to avoid unjustified detection of non-compliant provision of FCR. The under-fulfilment granted between 30 and 50 s is acceptable, since most RP cannot exactly achieve the set-point due to noise (see Section 3.3). In addition, a large part of the FCR has already been activated, which is why the slight under-fulfilment that is granted is not decisive for system stability. It may seem that the slow bound is overly strict for $10s < t < 15s$, as the slow bound is above the minimum requirement. However, note that the SO-GL also specifies that an artificial delay is not permitted. To our knowledge, there is no RP that has a technically justified reaction time greater than 10 s after which it is able to increase FCR provision from 0 to 50 % within only further 5 s. Hence, the definition of the slow bound in (4) to (7) can be considered to be compatible with the SO-GL. Note that choosing a dynamical system with a time delay of 15 s would result in a reduction of the slow bound and, as a consequence, in significant under-fulfilment of the resulting slow bound, which would be deemed unacceptable with respect to system stability.

So far, we have discussed a single step change of the FCR set-point in one direction. However, the FCR set-point in real grid operation changes permanently and with frequently changing direction. In order to clarify the influence of changes in different directions on the tolerance channel, these are shown in Figure 5a by several step changes in different directions at an interval of 30 s. In contrast to the prequalification procedure (step changes in different directions at an interval of 15 min [2]), the slow bound does not reach steady state after this time. It becomes clear from Figure 5a that, when the upper bound changes from fast to slow bound after 60 s (due to the negative set-point step), there is an undesired step in the upper bound. This is due to the fact that the slow bound has not yet reached the FCR set-point before the negative set-point step takes place.

In order to correct this undesired behaviour, the dynamic system Σ is duplicated such that the output values of Σ_{UB} and Σ_{LB} are used for the upper and the lower bound, respectively. Σ_{UB} and Σ_{LB} then are reinitialized to a steady state corresponding to the current FCR set-point $P_{FCR,set}$. Thus, both systems are identical in terms of their parameters, but after a reinitialization their output variables differ because

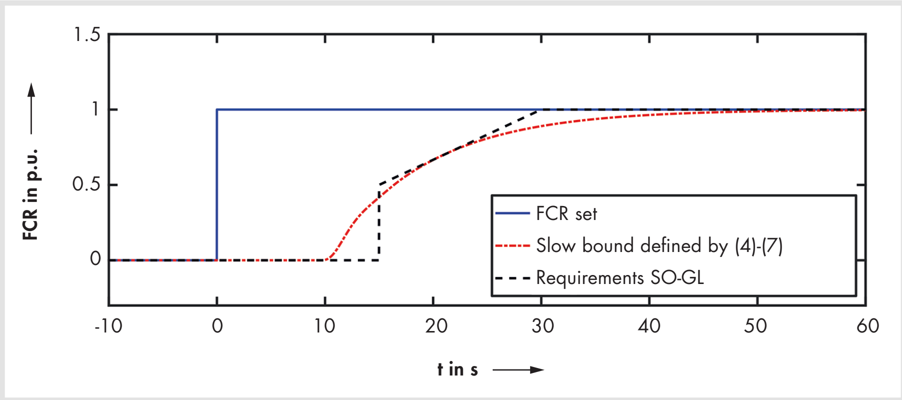

Fig. 4. Step response of the dynamical system for a positive FCR set-point step and SO-GL requirements [1].

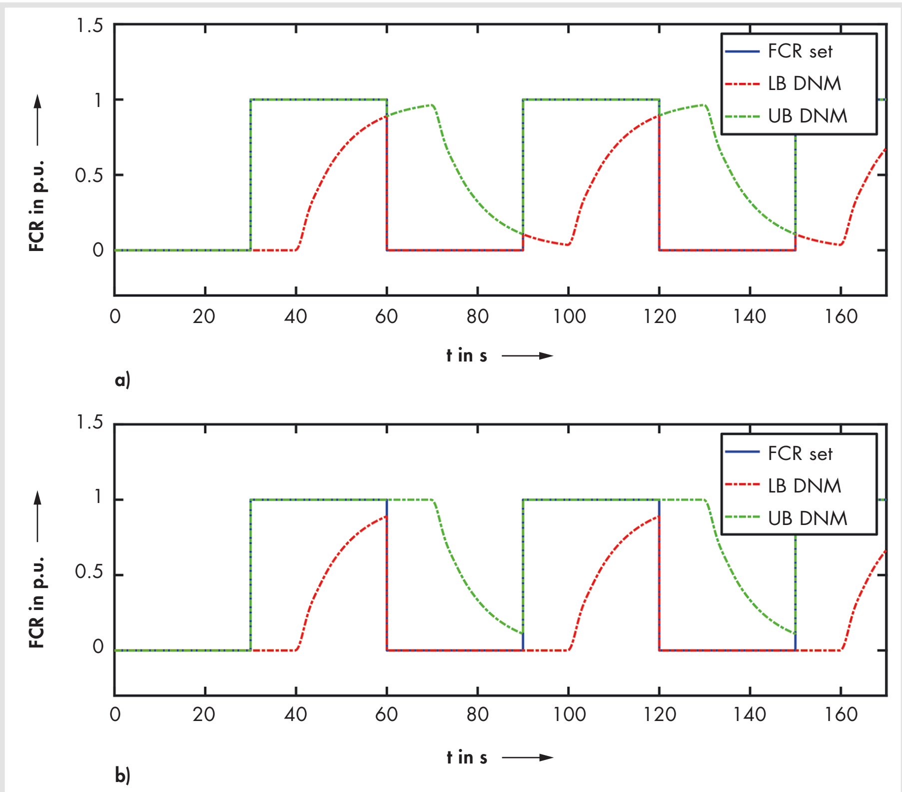

Fig. 5. a) Upper (UB) and lower bound (LB) of FCR activation for fast FCR set-point steps (30 seconds).
b) Upper (UB) and lower bound (LB) of FCR activation for fast FCR set-point steps with reinitialization.

different histories of the FCR set-point are taken into account.

The reinitialization is carried out at time t_r for the upper bound if

$$P_{out,UB}(t_r) \leq P_{FCR,set}(t_r) \wedge \dot{P}_{FCR,set}(t_r) < 0, \qquad (8)$$

and for the lower bound if

$$P_{out,LB}(t_r) > = P_{FCR,set}(t_r) \wedge \dot{P}_{FCR,set}(t_r) > 0, \qquad (9)$$

where $P_{out,UB}$ and $P_{out,LB}$ are the outputs of Σ_{UB} and Σ_{LB}, respectively.

The reinitialization at time t_r is performed by setting the current and past state vector x of $\Sigma_{UB/LB}$ to

$$x(t \leq t_r) = [P_{FCR,set}(t_r)\ 0\ 0)]^T \qquad (10)$$

This state vector corresponds to a steady state $P_{out} = P_{FCR,set}$ for the input $P_{FCR,set}$. Moreover, setting also the values for the past means that the output of $\Sigma_{UB/LB}$, i.e. the respective bound, is retained at $P_{FCR,set}(t_r)$ until $t_r + T_d$, even if $P_{FCR,set}(t)$ changes, as long as the reinitialization conditions (8) and (9) are not met (which would again cause a reinitialization).

Figure 5b shows the effect of reinitialization on the tolerance channel. After 60 s, condition (8) is true and a reinitialization takes place. The state of Σ_{UB} is set to the FCR set-point of the current time step. This allows the RP appropriate reaction time for the power reduction.

Figure 3b shows the tolerance channel for the FCR set-point curve from Figure 3a. The upper and lower bound $P_{UB/LB,0}(t)$

result from the maximum (UB) or minimum (LB) from $P_{FCR,set}(t)$ (fast bound) and $P_{out,UB/LB}(t)$ (slow bound). The reinitializations become visible at maximum and minimum values of the FCR set-point. The resulting tolerance channel is as desired. The FCR activation of the pumped storage power plant is also shown. Although the tolerance bounds are violated in a few time steps, FCR activation by the RP is compliant in general. The violations can be traced back to noise in the power activation, which occurs in real operation due to disturbances in the process (e.g. pressure surges in pumped storage power plants, fuel inhomogeneities in steam power plants, etc.). To allow for a realistic evaluation of the monitoring methodology, noise was added to the FCR activation of the power plant model.

3.3 Minimum tolerance channel width

According to (4) to (10), time periods with almost no frequency change cause the tolerance channel bounds to converge. As a result, noisy RP would be classified as non-compliant without reasonable justification, especially in times with small frequency changes.

A minimum tolerance channel width can allow for a certain amount of noise (up to 5 % of the offered FCR). The upper and lower bound with minimum tolerance channel width $P_{UB/LB,5}$ are calculated as

$$P_{UB,5}(t) = \max(P_{UB,0}(t); P_{MV,0}(t) + 0.05; P_{FCR,set}(t)+0.05) \quad (11)$$

$$P_{LB,5}(t) = \min(P_{LB,0}(t); P_{MV,0}(t) - 0.05; P_{FCR,set}(t) - 0.05) \quad (12)$$

where $P_{UB/LB,0}$ is the upper / lower bound without minimum tolerance channel width as calculated according to Section and

$$P_{MV,0}(t) = \frac{1}{2} \cdot (P_{UB,0}(t) + P_{LB,0}(t)). \quad (13)$$

The minimum tolerance channel width provides a minimum distance both to $P_{MV,0}$, which ensures that slow RP do not violate the tolerance channel bounds only due to a small amount of noise, and to $P_{FCR,set}$ (for fast RP).

Due to the definitions in (11) and (12), however, there is a rapid transition from the slow bound with minimum tolerance channel width to the slow bound without minimum tolerance channel width in the case of rapid FCR set-point changes (see red dotted line in Figure 6 after 0 s as an example). These rapid changes could lead to measured values outside the tolerance channel, which would therefore be considered non-compliant, if the FCR activation was previously in the lower (positive set-point step) or upper (negative) range of the tolerance channel. Therefore, in (14) and (15), the difference between the bounds of the tolerance channels with and without minimum tolerance channel width, i.e. $P_{UB,5} - P_{UB,0}$, is delayed by the transfer function $G(s) = \frac{1}{(0.5 \cdot s+1)^3}$ in order to smooth the transition:

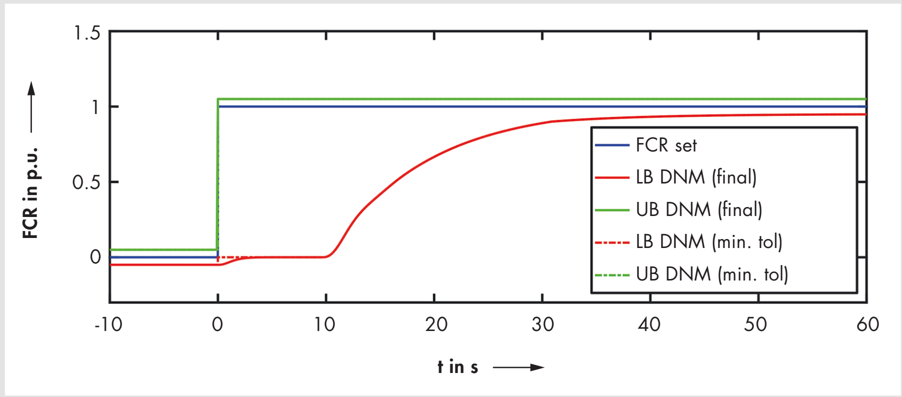

Fig. 6. Minimum tolerance channel width with (final) and without transition (min. tol) for a FCR set-point step.

$$\Delta P_{UB,del}(s) = G(s) \cdot (P_{UB,5}(s) - P_{UB,0}(s)) \quad (14)$$

$$\Delta P_{LB,del}(s) = G(s) \cdot (P_{LB,5}(s) - P_{LB,0}(s)) \quad (15)$$

Since the tolerance channel should not be narrowed by this delay, an additional maximum/minimum calculation is carried out with $P_{UB,LB,5}(t)$ in order to arrive at the final definitions for the upper and lower bound:

$$P_{UB,f}(t) = \max(P_{UB,5}(t); P_{UB,0}(t) + \Delta P_{UB,del}(t)) \quad (16)$$

$$P_{LB,f}(t) = \min(P_{LB,5}(t); P_{LB,0}(t) + \Delta P_{LB,del}(t)) \quad (17)$$

Figure 6 displays the lower bounds $P_{LB,5}$, resulting from (12), and $P_{LB,f}$, including the additional transition and resulting from (17). It can be seen that the sudden change in $P_{LB,5}$ is smoothed by the transition such that the RP is granted sufficient reaction time.

Figure 3c shows the final tolerance channel for the FCR set-point shown in Figure 3a. Now, all data points are within the tolerance channel, since the new tolerance bounds allow for a certain level of noise.

3.4 Consideration of a frequency filter

This section deals with the optional consideration of a possible frequency filter by a modification of the FCR set-point $P_{FCR,set}$. Due to space limitations, only the regulatory framework and implementation are discussed here and no simulation results are shown. The tolerance channels in the previous sections have been calculated without taking any frequency filter into account.

According to Annex V SO-GL, a combined effect of inherent frequency response insensitivity and a possible frequency response dead band of 10 mHz is permissible for the provision of FCR [1]. This should also be taken into account in the context of monitoring. Therefore, the effects of a 10 mHz moving dead band (assuming no inherent frequency response insensitivity) on FCR monitoring is considered and the monitoring procedure is adjusted accordingly. Figure 7 shows a typical dead band reported to be used in conventional power plants [8]. Typical parameters for the provision of FCR are:

– Dead band: c_F=10 mHz
– Filter time constant: T_F=30 up to 600 s

For FCR monitoring, filter time constants between T_F=30 s and T_F=100 s (common range) are considered.

In order to create a tolerance channel that takes a possible frequency filter into account, the set-point that is used as input for the calculation of the bounds by (4) – (10) is calculated from the following FCR set-points:

– $P_{FCR,set}(\Delta f)$, based on the actual frequency deviation,

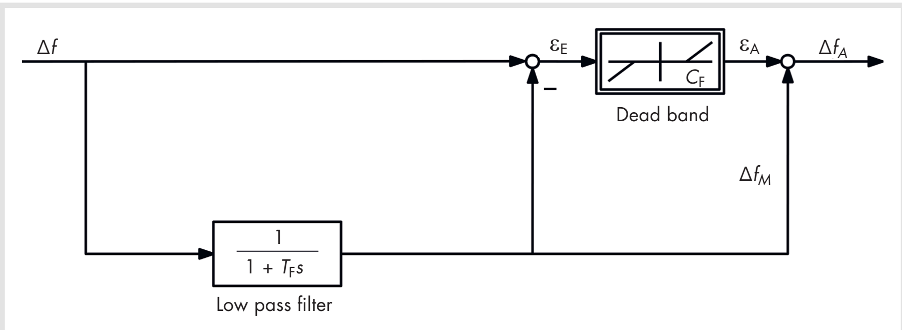

Fig. 7. Moving dead band according to [8].

– $P_{FCR,set}(\Delta f_{A30/100})$, based on the the frequency deviation filtered by a moving dead band with $T_F = 30\,s$ or $100\,s$,

as follows:

$$P_{FCR,set,UB} = \max\big(P_{FCR,set}(\Delta f);\; P_{FCR,set}(\Delta f_{A30});\, P_{FCR,set}(\Delta f_{A100})\big) \quad (18)$$

$$P_{FCR,set,LB} = \min\big(P_{FCR,set}(\Delta f);\; P_{FCR,set}(\Delta f_{A30});\, P_{FCR,set}(\Delta f_{A100})\big) \quad (19)$$

Thus, the set-point is not necessarily identical for the two bounds. These set-points then can be used as inputs for Σ_{UB} and Σ_{LB} without any further modification of the procedure described in the previous sections.

3.5 Evaluation of the tolerance channel for a longer time period

The tolerance channels presented in Section and 3.3 can be used to check whether the activation of FCR is compliant at the respective time step. For a product period of the FCR activation (four hours since 1 July 2020), however, an overall evaluation of the compliance of FCR activation is difficult. Therefore, this section proposes an evaluation method for longer time periods.

The aim of the evaluation is to summarize the results for a longer time period in a clear graph. The evaluation method should also indicate the type of non-compliance.

As a first step, the results of the former sections are normalized. This allows a comparison of FCR activation at different time steps and with different tolerance channel widths. It is useful to define a reference value for the representation in a graph. In this case, the mean value of the final tolerance channel $P_{MV,f} = 0.5 \cdot (P_{UB,f} + P_{LB,f})$ is used for this. This value also provides information about the expected FCR activation and is therefore helpful for the determination of the type of non-compliance in the further process.

When normalizing the deviation of the FCR activation $P_{FCR,act}$, its difference to the mean value of the final tolerance channel $P_{MV,f}$ is normalized to half the final tolerance channel width:

$$d_{norm} = \frac{P_{FCR,act} - P_{MV,f}}{P_{MV,f} - P_{LB,f}} \quad (20)$$

The normalized deviation d_{norm} enables the following classification for each measured value $P_{FCR,act}$:

- $|d_{norm}(t)| > 1$: larger than upper ($d_{norm}(t)| > 1$) or smaller than lower bound (d_{norm} (t)<–1), therefore $P_{FCR,act}$ is not compliant.
- $|d_{norm}(t)| \leq 1$: within the tolerance channel, thus compliant.

It should be noted that smaller values of $|d_{norm}(t)|$ are not generally considered as better, since the mean value of the final tolerance channel $P_{MV,f}$ does not correspond to ideal FCR activation. Rather, it is only used as a reference value. In particular, perfect activation, i.e. following the set-point without delay, would not lead to d_{norm}. Therefore, all values $|d_{norm}(t)| \leq 1$ are to be regarded as equivalently compliant. However, if $|d_{norm}(t)| > 1$, the value of $d_{norm}(t)$ gives an indication on how severe the non-compliance is.

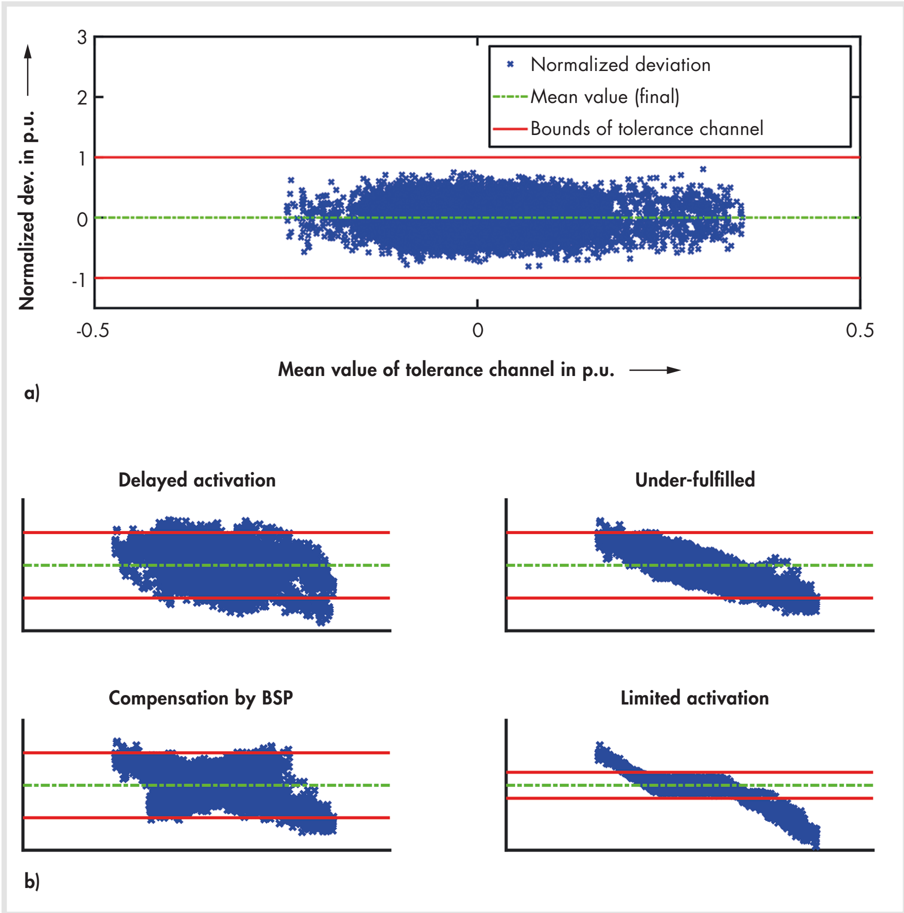

Fig. 8. a) Evaluation for a longer time period.
b) Evaluation for different types of non-compliance with FCR requirements.

Figure 8a shows the evaluation of the pumped storage power plant for a time period of four hours without considering a frequency filter. The mean values of the final tolerance channel $P_{MV,f}$ are plotted on the x-axis and the associated values of the normalized deviation d_{norm} on the y-axis. Since the RP complies with FCR requirements, all values are within the range [–1,1].

3.6 Results for different non-compliant FCR activations

This section presents the evaluation graphs for various types of non-compliance with the SO-GL requirements (Figure 8b) and explains how these can be assigned using the graphs. The graphs are only intended to provide a qualitative overview and are therefore shown without axes labels. The axes are identical to Figure 8a.

The graph at the top left shows delayed FCR activation. In this case, violations of the tolerance channel occur for all mean values of the final tolerance channel, since delayed activation is independent of the mean value.

In the graph at the top right, FCR activation is insufficient. The gain factor of FCR activation in the model of the RP is at 80 % of the required gain. In this case, there are no violations of the tolerance channel in the case of absolute mean values that are very small, since the impact of the gain remains within the tolerance channel width. In the case of large absolute mean values, however, violations can be observed. Due to the gain being too small, the result is a straight line sloping down to the right.

At the bottom left, a superimposition of under-fulfilment with subsequent over-fulfilment (120 % of the required gain) can be seen. This results in an “X”-shape in the graph as the under-fulfilment is superimposed with a straight line from the over-fulfilment that is inclined to the lower left.

In the last case, the FCR activation is limited to 10 % of the offered FCR in both directions. It can be seen that the activation is compliant for absolute mean values below 0.1. For larger absolute mean values, the deviations increase rapidly, since the FCR activation is not increased or decreased further.

The results in Figure 8b show that the evaluation method is able to distinguish different cases of non-compliance.

4 Conclusion

In this article, a methodology for the separation of the scheduled power, FCR, aFRR, and mFRR is presented, which is necessary to extract the activation of each product in order to use it for monitoring. For this purpose, a dynamic activation model is determined for each product, solely based on measurement data, which models the provision in the best possible way. Results for available real data show deviations from the real behaviour, but they are significantly more precise and adequate than previous methods.

The part of the "Dynamic Normalization Methodology" (DNM) monitoring concept presented here enables automatic monitoring of FCR activation during operation. It overcomes shortcomings of existing proposals, in particular with respect to the dynamic requirements for FCR activation. For this purpose, tolerance channels are formed based on the slowest permitted reaction of a RP. In order to allow for a certain level of noise in the output power of the RP, a minimum tolerance channel width is introduced. A possible frequency filter can also be taken into account by adjusting the FCR set-point for the respective bound. In the subsequent evaluation of the results with a normalization, a clear representation of the quality of FCR activation for longer time periods is made possible. This allows conclusions to be drawn about the type of non-compliance.

The methods presented are currently being tested with real data by TransnetBW (TSO).

References

[1] European Commission, *COMMISSION REGULATION (EU) 2017/1485 – of 2 August 2017 – establishing a guideline on electricity transmission system operation,* 2017. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017R1485&from=LT

[2] 50hertz, amprion, Tennet, TransnetBW, *Revised prequalification requirements (FCR, aFRR, mFRR)* [in German], 2020. [Online]. Available: https://www.regelleistung.net/ext/download/PQ_Bedingungen_FCR_aFRR_mFRR

[3] 50hertz, amprion, Tennet, TransnetBW, *Revised rules for the determination of instantaneous balancing power* [in German], 2018. [Online]. Available: https://www.regelleistung.net/ext/download/Konsultation_Regelleistungsistwerte

[4] RTE,"*Règles Services Système Fréquence, 2018*. [Online]. Available: https://www.services-rte.com/files/live/sites/services-rte/files/pdf/role-gestionnaires/20181026_Regles_services_systeme_frequence.pdf

[5] NERC, *Reliability Guideline – Primary Frequency Control,* 2019. [Online]. Available: https://www.nerc.com/comm/OC/RS_GOP_Survey_DL/PFC_Reliability_Guideline_rev20190501_v2_final.pdf

[6] P. Maucher and H. Lens, *Monitoring the Compliance of Balancing Reserves Power with the System Operation Guideline of Continental Europe,* Submitted for presentation at IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids, 2021.

[7] P. Maucher and H. Lens, *Monitoring the Compliance of Frequency Containment Reserves Activation with the System Operation Guideline of Continental Europe,* in ETG-Kongress, virtual, 2021.

[8] T. Weissbach and E. Welfonder, *Frequenzfilterung bei der Primärregelung – Vor- und Nachteile für den Kraftwerks- und Netzbetrieb,* in VGB-Konferenz „Elektrotechnik, Leittechnik, Informationsverarbeitung" (KELI), Dresden, 2010.