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Options for the Implementation of Fast Control Reserves in the Continental European Power System

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Abstract

Increasing penetration of power electronics interfaced generation (PEIG) raises several challenges for the operation, control and protection of power systems. Due to the rapid transition towards renewable energy sources (RES) based power systems, conventional generation facilities using synchronous generators (SG) tend to be “out of merit”. The associated reduction of SG based generation leads to a decreasing network time constant (T_A), which corresponds to the overall inertia in the system. Contrary to SG based generation, which provides inertia to the system inherently and therefore effectively counteracts large gradients in the system frequency (rate of change of frequency, RoCoF), PEIG by default do not provide inertia. As a result, power systems will become more prone to frequency instabilities as conventional frequency containment reserves (FCR) will not be able to stabilize the frequency in the event of a sudden power imbalance. In order to address future frequency stability problems different long- and short-term mitigation measures exist.

This paper investigates options for the implementation of fast control reserves in the Continental European (CE) power system, which are being developed and examined within the frame of the R&I project *Advanced Balancing Services for Transmission System Operators* (ABS4TSO).

In the first part of this paper, the fast control reserve concepts *FCR+, Enhanced Frequency Response* (EFR), *Synthetic Inertia* (SI) and *Fast Active Power Injection* (FAPI) are described. Furthermore, their impact on the frequency stability is evaluated based on a simulation model of the CE power system, considering a reference incident (imbalance) equal to 3 GW as defined in the System Operation Guideline.

In the second part of this paper, the fast control reserve concepts are evaluated with regard to market and regulatory aspects. The pros and cons of the different implementation options are presented and a possible implementation roadmap is shown, based on current observations, future scenarios and simulation results of the CE power system.

Keywords: Fast Control Reserves, Enhanced Frequency Response, Synthetic Inertia, Fast Active Power Injection, Frequency Containment Reserves, Balancing services

Introduction

Historically, power systems are primarily based on conventional generation facilities, which feed into the grid via synchronous generators (SG). SG possess a rotating mass that helps to limit large gradients in the system frequency (rate of change of frequency, RoCoF) in case of sudden power imbalances in the system. However, recent trends show a decrease of the share of conventional generation facilities and an increasing penetration of power electronics interfaced generation (PEIG) [1] [2]. Unlike SG, PEIG do not inherently provide inertia, unless they are operated under specially designed control schemes. This trend leads to a decrease of the network time constant (T_A), which is a measure for the overall inertia in the system. As a result, power systems will become more prone to frequency instabilities [3] and the question arises, whether the conventional frequency containment reserves (FCR) will be sufficient to adequately stabilize the frequency in the future.

Figure 1 shows simulated frequency curves for a simplified model of the Continental European (CE) power system, considering the "*CE Design Hypothesis*" [4] and conventional FCR for different values of T_A but not taking into account further emergency functionalities of the power system such as shedding of industrial loads or pumps above 49 Hz. For values of T_A < 10 s the frequency drops below the dynamic security limit of 49.2 Hz, if the power imbalance is equal to the reference incident of 3 GW, as defined in the System Operation Guideline [5]. For values of T_A < 6 s the frequency drops below 49 Hz, which is the current limit for load shedding in the CE power system. Since such values of the network time constant are likely to occur in the future, different long- and short-term mitigation measures should be considered.

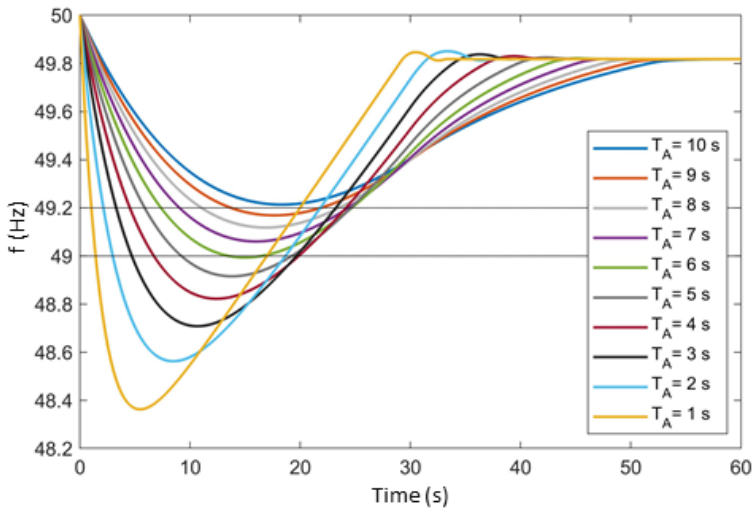


FIGURE 1: SIMULATED FREQUENCY CURVES FOR DIFFERENT NETWORK TIME CONSTANTS (SYSTEM SIZE = 150 GW, SELF-REGULATING EFFECT OF THE LOADS = 1 %/HZ, POWER IMBALANCE = 3 GW)

The aim of this paper is to investigate and summarize options for the implementation of fast control reserves in the CE power system, which are developed and examined within the frame of the R&I project Advanced Balancing Services for Transmission System Operators (ABS4TSO) [6].

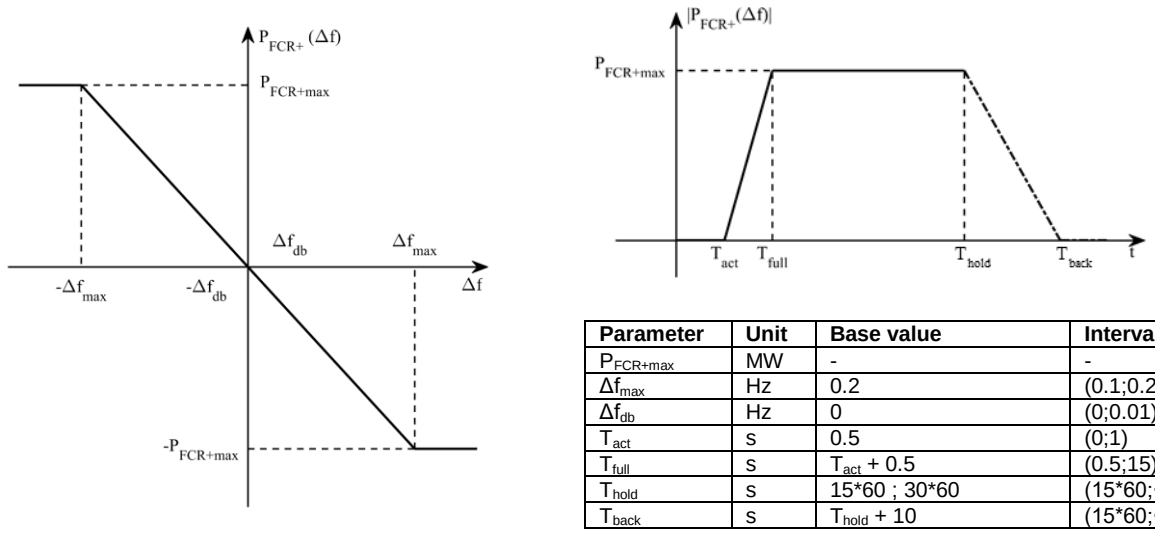
1. Development and evaluation of fast control reserve concepts

This section theoretically describes four novel fast control reserve concepts: *FCR+*, *Enhanced Frequency Response* (EFR), *Synthetic Inertia* (SI) and *Fast Active Power Injection* (FAPI). Firstly, the frequency and time characteristic curves as well as the range of

the related parameters are defined. The influence of these parameters is investigated by means of a single-area simulation model (MATLAB/SIMULINK) of the CE power system. A reasonable range for each parameter is selected with regard to technical feasibility considerations and finally a base value is chosen after conducting a sensitivity analysis. In addition, the effectiveness and technical aspects of the different fast control reserve concepts are evaluated.

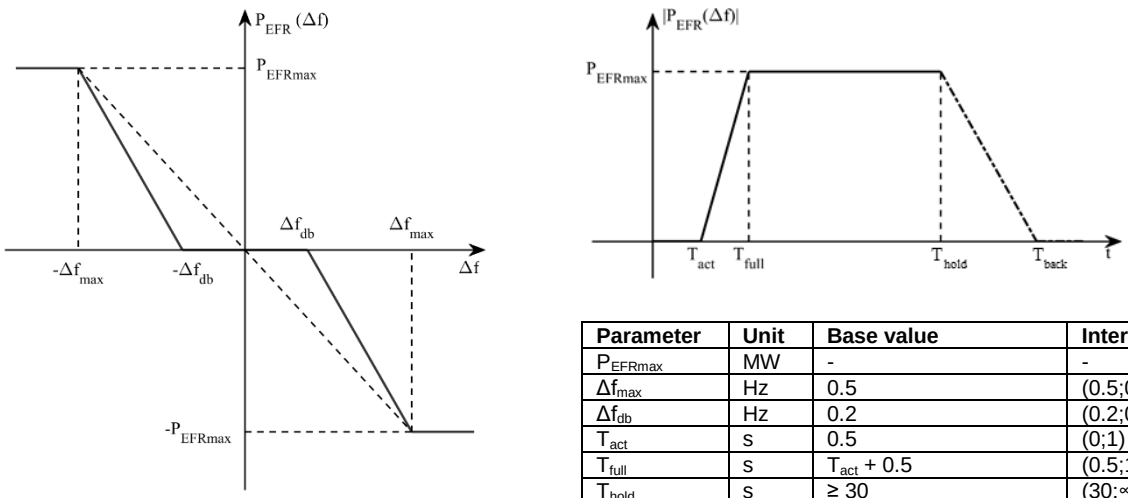
FCR+ and EFR

FCR+ and EFR are both designed to be activated proportional to the frequency deviation. FCR+ is intended as part of the already existing FCR (3 GW) but is activated significantly faster than conventional FCR, which have to be fully activated within 30 s in the CE power system [5]. Accordingly, the current FCR would be separated into conventional FCR and FCR+. Contrary to FCR+, EFR in this paper is intended as an independent fast control reserve that is only activated at a frequency deviation of more than ± 200 mHz. Accordingly, EFR would be added to the already existing FCR. The corresponding characteristic curves and parameters of FCR+ and EFR are shown in Figure 2 and Figure 3.



Parameter	Unit	Base value	Interval
$P_{FCR+max}$	MW	-	-
Δf_{max}	Hz	0.2	(0.1;0.2)
Δf_{db}	Hz	0	(0;0.01)
T_{act}	s	0.5	(0;1)
T_{full}	s	T_{act} + 0.5	(0.5;15)
T_{hold}	s	15*60 ; 30*60	(15*60;∞)
T_{back}	s	T_{hold} + 10	(15*60;∞)

FIGURE 2: CHARACTERISTIC CURVES AND PARAMETERS OF FCR+

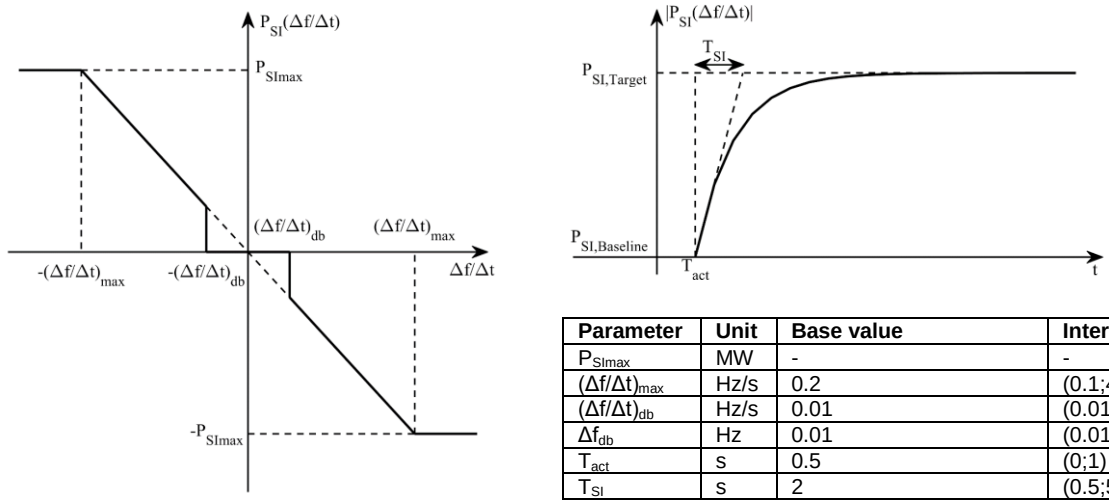


Parameter	Unit	Base value	Interval
P_{EFRmax}	MW	-	-
Δf_{max}	Hz	0.5	(0.5;0.8)
Δf_{db}	Hz	0.2	(0.2;0.5)
T_{act}	s	0.5	(0;1)
T_{full}	s	T_{act} + 0.5	(0.5;15)
T_{hold}	s	≥ 30	(30;∞)
T_{back}	s	T_{hold} + 5	(35;∞)

FIGURE 3: CHARACTERISTIC CURVES AND PARAMETERS OF EFR

SI

SI is intended to emulate an inertial response through a change in power, dependent on the RoCoF (passive synthetic inertia [7]). The corresponding characteristic curves and parameters of SI are shown in Figure 4. SI power is activated whenever both the frequency deviation and RoCoF are outside their respective deadbands Δf_{db} and $(\Delta f/\Delta t)_{db}$. The activation dynamics of SI are based on a first order behavior. Since a number of PEIG already try to emulate an inertial response provided by SG, their behavior may be altered by modifying their control scheme in order to improve its effectiveness. One option to achieve this is to implement a zone-selective control of SI, dependent on both the frequency deviation (Δf) and the RoCoF ($\Delta f/\Delta t$) [8].

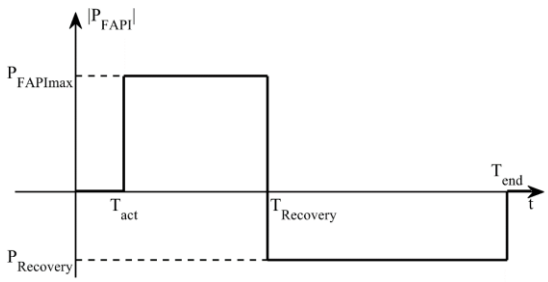


Parameter	Unit	Base value	Interval
P_{SImax}	MW	-	-
$(\Delta f/\Delta t)_{max}$	Hz/s	0.2	(0.1;4)
$(\Delta f/\Delta t)_{db}$	Hz/s	0.01	(0.01;2)
Δf_{db}	Hz	0.01	(0.01;0.2)
T_{act}	s	0.5	(0;1)
T_{SI}	s	2	(0.5;5)

FIGURE 4: CHARACTERISTIC CURVES AND PARAMETERS OF SI

FAPI

FAPI is intended to support existing control reserves by means of a static power adjustment, which is triggered by exceeding a defined frequency deviation. Since FAPI is triggered once the frequency deviation exceeds a certain threshold, it has an activation curve, however no frequency-dependent characteristic curve. The corresponding time response upon activation and parameters of FAPI are shown in Figure 5.



Parameter	Unit	Base value	Interval
$P_{FAPImax}$	MW	-	-
$P_{Recovery}$	MW	$P_{FAPImax}$ / 2	(0; $P_{FAPImax}$ / 2)
Δf_{db}	Hz	0.2	(0.01;0.3)
T_{act}	s	0.5	(0;1)
$T_{Recovery}$	s	T_{act} + 15	(5;20)
T_{end}	s	T_{act} + ($T_{Recovery}$ - T_{act}) * 2	(10;40)

FIGURE 5: TIME RESPONSE AND PARAMETERS OF FAPI

Sensitivity analysis and evaluation results based on a CE single-area simulation model

To gain a deeper understanding of the effectiveness of the fast control reserve concepts and assess the impact of their parameters, a sensitivity analysis has been conducted. This section presents only an excerpt of the sensitivity analysis conducted in [9]. The power values $P_{FCR+max}$, P_{EFRmax}, P_{SImax} and $P_{FAPImax}$ have been determined for selected parameter

sets via simulations with the single-area model, by identifying the required power to maintain a frequency above 49.2 Hz. The results are shown in Figure 6.

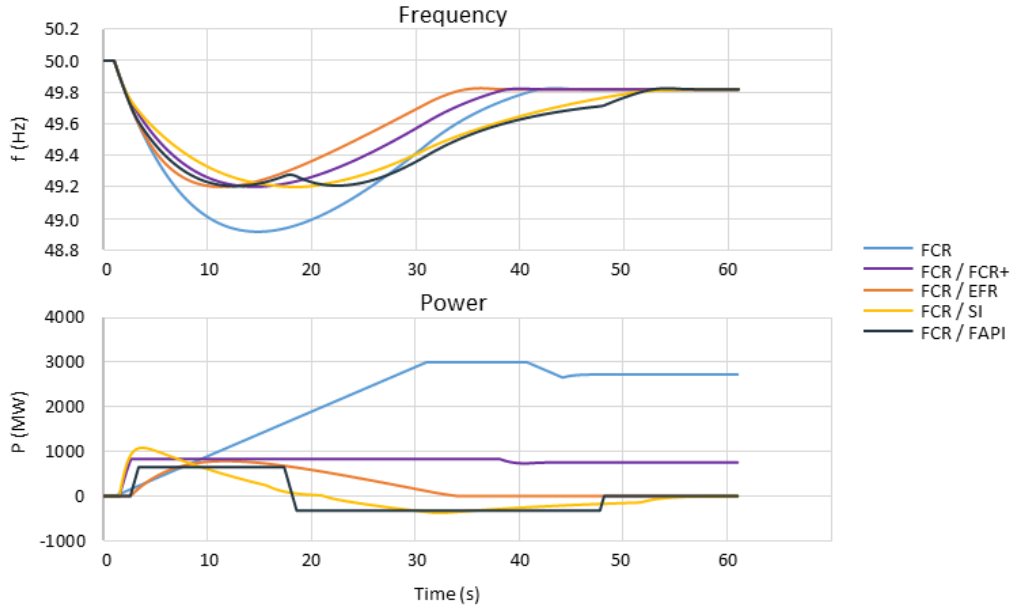


FIGURE 6: FREQUENCY AND POWER CURVES FOR DIFFERENT FAST CONTROL RESERVE CONCEPTS (SYSTEM POWER = 150 GW, SELF-REGULATION EFFECT OF THE LOADS = 1 %/HZ, POWER IMBALANCE = 3 GW, T_A = 5 S)

The results of the sensitivity analysis show that both FCR+ and EFR represent robust and fast control reserve concepts, as slight variations of the critical parameters do not have considerable impact on the overall performance. For this reason, FCR+ and EFR would be well suited for use as a fast control reserve. However, it has to be noted that the full activation time of FCR+ and EFR should not be set too high (T_{full} > 7.5 s) as this would lead to a significantly higher amount of required control reserves. The same principle applies to the parameters Δf_{db} and Δf_{max} of EFR.

Figure 6 shows that SI can improve the frequency stability and thus can help to keep the frequency above the 49.2 Hz dynamic security limit. Furthermore, it is clearly visible that SI improves the inertial response of the system as it limits the RoCoF and delays the frequency nadir. However, without a zone-selective control, it also delays the frequency recovery after the nadir since it limits the RoCoF during the recovery period. Generally, it can be concluded that the definition of the SI characteristics and the specification of its parameters, especially those regarding the frequency gradient, is not a trivial task and requires thorough research. In addition, SI requires a rather high sampling rate and robust filtering of both frequency and power. Possible measurement delays or outliers could otherwise lead to undesired instabilities [3].

Compared to the other fast control reserve concepts, FAPI shows both the largest dependence on the simulation cases examined and the largest influence of specific parameters on the frequency response. This is due to its static and uncontrolled activation as well as to the recovery period, which causes a second frequency nadir. In particular, the choice of the parameters $P_{FAPImax}$ ($P_{Recovery}$ is given by this) and $T_{Recovery}$ has a strong influence. Too high values of $P_{FAPImax}$ and hence $P_{Recovery}$ could even lead to a critical second frequency nadir, thus counteracting the existing control reserves and endangering the whole power system. These aspects may lead to the conclusion that FAPI tends to be less suitable to be implemented as a fast control reserve in the CE power system.

2. Options for the Implementation in the CE power system

Besides the theoretical development of fast control reserve concepts, the question arises how they should be introduced in a power system. According to Figure 7, two general options exist to achieve the desired system behavior.

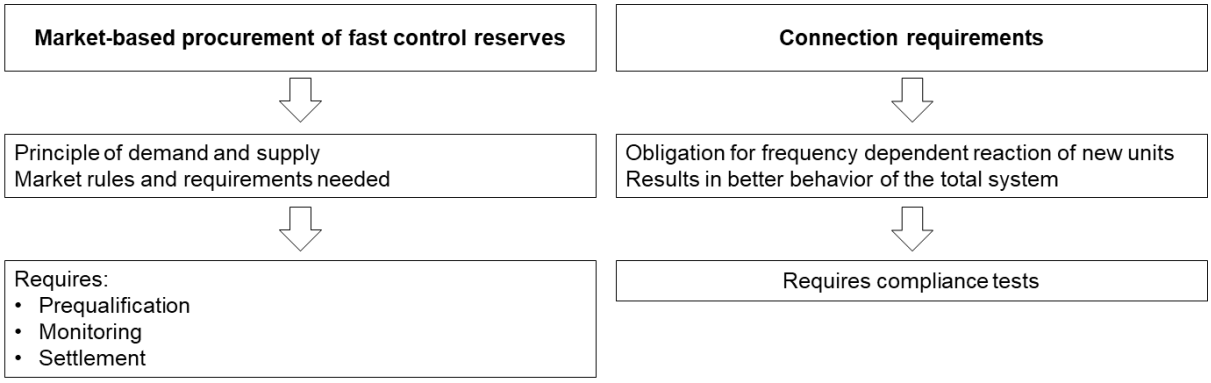


FIGURE 7: OPTIONS FOR THE IMPLEMENTATION OF FAST CONTROL RESERVES IN THE CE POWER SYSTEM

The first option guarantees the desired system behavior via a market-based procurement of fast control reserves – similar to already existing markets (e.g. for FCR). To organize a market, several aspects have to be considered, in particular the product design (maximum/minimum bid size, product period, conditional products, indivisible/divisible products, activation trigger, settlement, penalties, etc.), the prequalification of providers / reserve providing units (RPU) / technical entities (TE) and the monitoring of activation. Apart from that, the necessary regulatory framework (including respective market rules) has to be established. Experiences with existing control reserves have shown that such development processes require adequate time and comprehensive cooperation between the relevant transmission system operators (TSO) and stakeholders. For example, if a new fast control reserve product is intended to be used in an entire synchronous area (SA), TSOs need to compile several aspects, such as common technical requirements, dimensioning rules for the total required amount, allocation keys and possible restrictions for the distribution. Furthermore, market participants would most likely request TSOs to organize a single market for the entire SA, which introduces additional challenges (e.g. establishment of a central tendering/optimization platform, cross-border procurement and settlement, harmonization of boundary conditions, etc.).

While markets have the advantage that TSOs are able to constantly procure and monitor the necessary amount and quality of fast control reserves they may also introduce cost-inefficiencies, if the respective product design and remuneration system are not well suited. In addition, an illiquid market could potentially lead to operational challenges due to missing bids and hence insufficient amounts of fast control reserves.

To address these issues the second option is to mandatory require the necessary system behavior (technical capability) from new and substantially modified RPU/TE. This can be achieved with the introduction of new or extended connection requirements in dedicated Connection Network Codes (CNC) [10] [11]. The implementation of this option might be easier, as it does not require additional market rules. However, an agreement on harmonized connection requirements for the entire SA is also a time-consuming task, which needs to be well organized. Within this context, the scope (size and/or technology of RPU/TE) and a general framework (trigger for activation, parameters for the activation itself, etc.) has to be first set up on a SA level and then specified in national grid codes. Besides,

the current CNC legislation [10] [11] would also require the TSOs to validate the compliance of RPU/TE in the course of the connection process. Contrary to a market where the required behavior may be organized by aggregation (pooling) of individual RPU/TE with different connection points, mandatory connection requirements can only be defined on the level of a single RPU/TE.

Summarizing the mentioned aspects, it is not yet clear which option should be prioritized as a mitigation measure. Probably, a combination of a market-based procurement and new or extended connection requirements could be developed to find the most efficient and technology-neutral solution in the CE power system.

Description of the CE-2030+ implementation scenario

In order to obtain future recommendations for the introduction of fast control reserve concepts, different implementation scenarios have to be developed and evaluated. This section presents an analysis of an exemplary implementation scenario ("*CE-2030+*"), which is based on parallel developments in other SAs [12] [13] and estimations of the network time constant in the CE power system.

In this paper, the network time constants (T_A), for the CE-2030+ implementation scenario, are estimated with a dedicated electricity market model of the CE power system (Electricity Dispatch Optimization & Balancing Market Model [14]). The input data for the market model is derived from the TYNDP 2020 scenarios "*National Trends*" (NT) and "*Global Ambition*" (GA) [15]. For the purpose of comparison, estimations of T_A for the years 2017 to 2019 have been additionally performed using CE generation data from the ENTSO-E Transparency Platform [16].

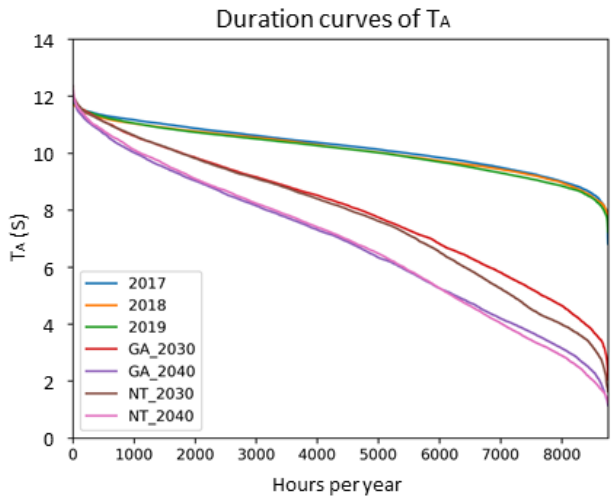


FIGURE 8: ANNUAL DURATION CURVES OF THE CURRENT AND FUTURE NETWORK TIME CONSTANT

Figure 8 shows a comparison of the annual duration curves of T_A for the years 2017 to 2019 and the CE-2030+ implementation scenario, which takes into account the TYNDP 2020 scenarios "*National Trends*" (NT) and "*Global Ambition*" (GA) [15]. As can be seen, the implementation scenario shows a significantly decreasing and more volatile network time constant. The decrease and the greater volatility of T_A is directly linked to the increasing amounts of PEIG/RES. For approximately 30 % of the scenario years NT2030 and GA2030, T_A becomes smaller than 6 s, which could potentially lead to critical frequency drops below 49 Hz (see Figure 1), if no other mitigation measures are active. Correspondingly, the number of possible critical frequency events increases up to approximately 40 % in the scenario years NT2040 and GA2040.

To gain a deeper understanding of future characteristics in the CE power system, a detailed distribution analysis of the network time constant has been additionally performed with the existing data basis. The distribution of T_A in the year 2019 and in the GA 2030 scenario is shown in Figure 9.

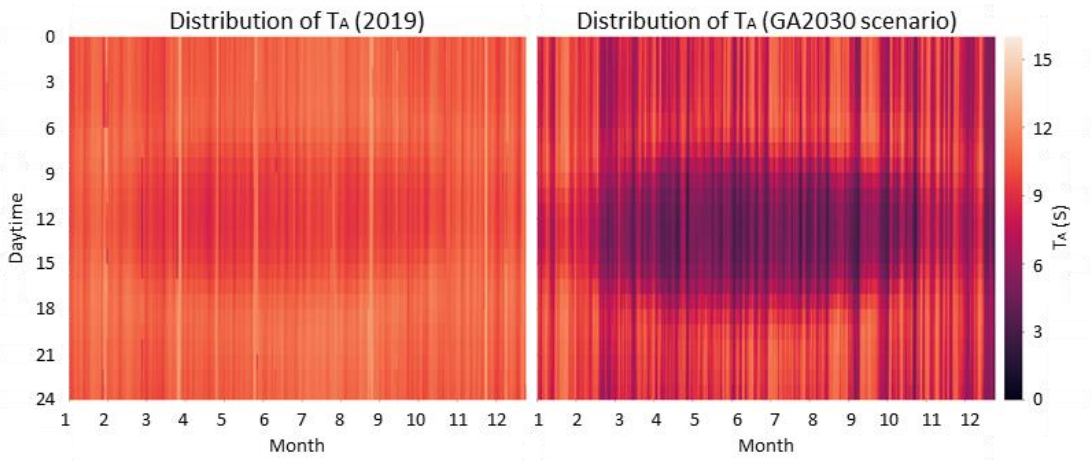


FIGURE 9: DISTRIBUTION OF THE NETWORK TIME CONSTANT IN THE YEARS 2017 TO 2019 AND IN THE GA 2030 SCENARIO

In the year 2019, a decrease of T_A (dark spot in the center of the graph) is already slightly visible, which is mainly caused by the infeed from inverter-based photovoltaic (PV) installations. With the increasing number of inverter-based PV installations in the CE power system, this effect becomes more evident in the scenario year GA2030. Furthermore, the pattern of T_A in the scenario year GA2030 additionally reveals dark vertical lines, which can be characterized by a high infeed from wind power.

The estimations of the future network time constant in the CE power system, shown in Figure 8 and Figure 9, clearly indicate the need of adequate mitigation measures to ensure frequency stability. Similar to [12] [13], the CE-2030+ implementation scenario assumes the introduction of either FCR+ or EFR via a market-based procurement as the most cost-efficient and effective mitigation measure. A detailed sensitivity analysis has shown that SI and FAPI are not necessarily required as long as T_A is greater than approximately 3 s [9]. Therefore, SI and FAPI are not utilized in the CE-2030+ implementation scenario, whereas they may be considered as additional mandatory connection requirements in long-term scenarios. Besides, based on the findings of Figure 9 and similar considerations from other SAs [12] [13], it can be assumed that FCR+ or EFR are more likely to be procured “dynamically” on a seasonal or, where appropriate, weekly or daily basis. However, it has to be noted that a highly dynamic and short-term dimensioning and procurement approach could potentially threaten reliability and planning security.

Evaluation of fast control reserve concepts in the CE-2030+ implementation scenario

The previous chapters and sections have shown that both FCR+ and EFR are technically suitable to be introduced via a market-based procurement in the CE-2030+ implementation scenario. Based on a detailed sensitivity analysis [9] the recommended technical values and necessary maximum amounts for the implementation of FCR+ and EFR are summarized in Table 1.

Parameter	FCR+	EFR
Full activation time	5 - 7.5 s	5 - 7.5 s
Maximum amount of fast control reserves	800 - 1400 MW	650 - 1400 MW
Conventional FCR	2200 - 1600 MW	3000 MW
Total amount of reserves	3000 MW	3650 - 4400 MW

TABLE 1: RECOMMENDED TECHNICAL VALUES AND NECESSARY MAXIMUM AMOUNTS OF FCR+ AND EFR

In this section, the fast control reserve concepts FCR+ and EFR are further evaluated with regard to market and regulatory aspects in the CE-2030+ implementation scenario. The results of the qualitative analysis are summarized in Table 2.

Aspect	FCR+	EFR
Level of implementation	As part of conventional FCR, FCR+ is a product for the entire SA.	Similar to FCR+, EFR can be primarily seen as a product for the entire SA. EFR may also be introduced at national level, if specific operational conditions require faster control reserves (e.g. TSOs at the border of the system with high shares of RES).
Regulatory framework Market rules (terms and conditions)	The introduction of FCR+ at least requires amendments of the System Operation Guideline and the SAFA (Annex A-1 "*Dimensioning rules for FCR*" and A-2 "*Additional properties for FCR*"). However, further necessary amendments of legislation (e.g. Balancing Guideline) cannot be excluded. FCR+ can be integrated in the existing FCR market rules.	The introduction of EFR as a product for the entire SA requires similar amendments as in the case of FCR+ and new market rules. The introduction of EFR as a national product may only require the establishment of new market rules.
Prequalification	FCR+ can be integrated into the existing FCR prequalification procedure. Existing RPU/TE can be also classified for FCR+ after a proof of the faster full activation time.	As a new separate product, EFR needs a dedicated prequalification procedure (it can, however, be structured similarly to the procedure of FCR).
Dimensioning approach	A dynamic dimensioning approach (based on forecasts) can be applied (this will, however, also have implications on the current FCR dimensioning approach). A too dynamic and short-term dimensioning approach could potentially threaten reliability and planning security.	A dynamic dimensioning approach (based on forecasts) can be applied. A too dynamic and short-term dimensioning approach could potentially threaten reliability and planning security.
Amount of fast reserves	FCR+ replaces a part of conventional FCR, the overall amount of reserves remains the same (3 GW).	EFR is used in addition to conventional FCR, the overall amount of reserves increases accordingly.
Deployment	Similar to conventional FCR, FCR+ is almost continuously active.	With Δf_{db} = ± 200 mHz EFR is only activated in usually rare events.
Energy-to-power (E/P)-ratio	FCR+ providers shall ensure to fully activate FCR+ continuously for a predefined time period (15/30 min). The E/P-ratio is determined according to this requirement.	Due to the fact that the frequency will recover and enter the range 50 ± 0,2 Hz almost immediately after the activation of EFR, it can be assumed that the E/P-ratio can be low.
Expected costs	The additional costs of FCR+ can be partly compensated with the decreasing costs of conventional FCR.	The introduction of EFR generates additional costs (based on the remuneration system, however, the additional costs may be negligible).
Business Model	Existing FCR providers can alternatively offer FCR+ or participate in the energy market.	EFR may be used as a product for new providers with alternative technologies, due to the low E/P-ratio and less activations. Due to the different product design of EFR, it can be assumed that EFR is not likely to be provided by existing FCR (RPU/TE).

TABLE 2: EVALUATION OF FCR+ AND EFR IN THE FRAME OF MARKET AND REGULATORY ASPECTS

From the findings in Table 2, it can be concluded that both FCR+ and EFR share common aspects and include equivalent advantages and disadvantages. FCR+ could be offered by some existing FCR providers, as different RPU/TE (e.g. battery storage) are capable to act faster than required by conventional FCR, without any or only minor modifications. Accordingly, this could simplify the market access and the prequalification process of FCR+, as only the faster full activation time needs to be adjusted and proved in the frame of an already well-established FCR prequalification process. Contrary, EFR could be a promising product for new providers with alternative technologies (e.g. fast switchable loads or storages with a low E/P-ratio). In this context, it has to be highlighted that this product may be designed asymmetrically to ensure the participation of a sufficient number of providers. Furthermore, EFR would require the establishment of a dedicated prequalification procedure.

4. Conclusions and recommendations

Recent trends show a decrease of the number of conventional generation facilities and an increasing penetration of PEIG. The associated reduction of SG, which inherently provide real inertia, leads to a decreasing network time constant and thus challenges in adequately maintaining the frequency stability in a power system. A possible way to counteract possible frequency stability issues could be the implementation of fast control reserves, which could be also provided by PEIG.

The fast control reserve concepts, developed in the frame of the R&I project ABS4TSO, consider either frequency-proportional (FCR+, EFR), RoCoF-proportional (SI) or static (FAPI) control strategies. As presented in this paper, all of the above-mentioned fast control reserve concepts can improve the frequency stability and can thus help to keep the frequency above the dynamic security limits. Regarding the technical aspects, FCR+ and EFR both represent robust and fast control reserve concepts, as slight variations of the critical parameters do not have a considerable impact on the overall performance.

To ensure the desired system behavior, either a market-based procurement of fast control reserves or the introduction of new or extended connection requirements may be considered.

An exemplary implementation scenario (“CE-2030+”), which is based on parallel developments in other SAs and estimations of the network time constant, shows that the introduction of either FCR+ or EFR via a market-based procurement can possibly be a cost-efficient and effective mitigation measure in the CE power system. The results of a qualitative analysis conclude that both FCR+ and EFR share common aspects and include equivalent advantages and disadvantages with regard to market- and regulatory aspects. FCR+ could be offered instantly by some existing FCR providers, whereas EFR could be a promising product for new providers with alternative technologies.

At this stage, a clear recommendation for a comprehensive implementation scenario in the CE power system cannot be provided. For all possible aspects, there is a need to consider a balance between the system needs, the capability of different technologies, the expectations from market participants and social welfare. Taking this into account, national or regional pilot projects, including TSOs, market participants, manufacturers and regulators, could serve as a promising basis to demonstrate the cost-efficiency and effectiveness of different fast control reserve concepts. Additionally, the outcomes from such pilot projects could be also used for the development of future regulatory frameworks in the CE power system.

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