Procurement of Frequency Stabilization in Decarbonized Power Systems

***Abstract*— Frequency stability of power systems is closely associated to inertia provided by synchronous machines in today's power systems. Yet the share of converter-based renewable power is steadily increasing. Thus, these units must contribute to immediate frequency stabilization in the future. The participation of renewable energy sources in fast reserve markets is already put into practice in some countries. However, the inherent reserve response through grid-forming control is not implemented on system-level. Technical simulations are promising, yet economic aspects, particularly the market design have not been discussed thoroughly. In this contribution, we assess different procurement schemes for frequency stabilization based on grid forming control, notably (i) network connection codes, (ii) market-based (auction) schemes and (iii) network operator assets. Our qualitative synopsis concludes that fully integrated network components lead to an inefficient provision and should only be used in transition periods. Network connection codes and market-based procurement schemes perform better from an economic perspective. Choosing between these options depends on the expected price of immediate frequency stabilization. In expectation of positive provision costs for this service, market auctions ensure a least cost provision mix. However, if (close to) zero costs for frequency stabilization are expected, the costs for market organization can be avoided while only relying on network connection codes. The findings of this work are fundamental to design, simulate and implement market-based procurement schemes in future.**

***Index Terms*—Converters, Power system economics, Power system stability, Resource management, Synchronous machines**

I. INTRODUCTION

A key challenge in the context of the decarbonization of electrical energy systems is the reduced amount of energy available for inertial response to disturbances. The reduction of rotating synchronous machines implies that supply-demand imbalances induce stronger and potentially more fatal frequency deviations that may lead into blackouts and thus should be avoided. Historically, inertial response is provided mainly by synchronous machines through the kinetic energy stored in the rotating shaft and is released inherently until the subsequent frequency ancillary services are deployed. Facing the decommissioning of fossil generation, alternatives, e.g., the provision of stabilization services through converter-based technologies are being explored, especially for countries where frequency stability issues are expected soon if no actions are taken. To abstain from technological particularities and to abstract from specific control schemes, we introduce the term Immediate Frequency Stabilization (IFS) as to designate a service of inherent response to power imbalances. IFS is faster than the other frequency stabilization services as depicted in Figure 1.

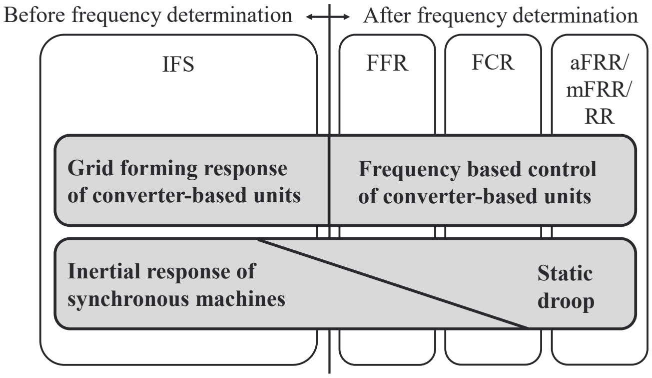

Figure 1. IFS as inherent service until reserve can additionally support based on a frequency estimate

Meanwhile, flexible solutions, particularly from converter-based devices are under research. Information and communication technology also underwent substantial progress. In future, smaller units of medium and low voltage networks may also play a more important role in supporting network stability. Any technical solution to enable the frequency stabilization using converter-based units will rely on modified control techniques. Various distinct control schemes have been proposed. As their use in the power system is only emerging, definitions of relevant capabilities are not fully agreed on yet. Therefore, related studies refer to different terms e.g., emulated inertia [1], synthetic inertia [2] or virtual inertia [3]. Discussions on the technical capability requirements of converters, relevant in designing network connection codes, often refer to Grid Following vs. Grid Forming Control (GFM). A crucial hurdle to implement frequency stabilization through converters has been the current limitation to prevent the converter modules to be damaged [4]. Even though there is no real-world experience on low-inertia power systems operated by a high number of GFM-controlled converters so far, simulations of system studies are available [5].

Market models for IFS have been proposed, such as co-optimization with reserve [6]. Pricing based on products with different quality is researched in [7]. The role of incentives for investments is presented in [8]. Especially in [9], a comparison of a regulatory and a market-based setup is performed. Meanwhile, real-world implementation trends are observable. National regulations, especially in regions with inertia shortage, are in debate. These programs aim to keep system security at an acceptable level in the near future. In Germany, remuneration is planned to foster refurbishing units to provide IFS. Still, above mentioned models and programs apply exemplary procurement schemes, and use specific product or capability definitions.

Given this context, we identify two research gaps: First, the selection of specific product characteristics of an IFS procurement scheme has not been scrutinized so far. Physical product properties, regional and temporal granularity must be set accordingly to prevent unwanted system behavior or costly oversupply. Second, discussions on efficient IFS procurement in the long-term i.e. fully decarbonized systems in 2045 and onwards, including the economically efficient pathway to this setup have not been discussed yet.

Therefore, this work responds to the following research questions: (a) What market design is preferrable from a techno-economic perspective in the long-run? (b) What influencing factors impact this decision on market design? Our main contribution is a synopsis of the possible IFS procurement schemes including the economic impact of each option on the system. Furthermore, we elaborate design choices of one possible procurement scheme in a decarbonized energy system. This groundwork is required for implementing a market simulation that can depict cost considerations more detailed.

This work is structured as follows: Section 2 explains the physical fundamentals. Section 3 revises recent developments in system operation. Section 4 discusses design choices for future frequency stabilization. Section 5 proposes a market-based procurement scheme. Section 6 discusses the work and Section 7 concludes.

II. FREQUENCY STABILIZATION

In traditional power system operation that relies on synchronous machines, the law of conversation of energy links mechanical torque and electrical power. The power system frequency behavior can be described by the swing equation, see Eq. 1. If a power imbalance between generation and demand occurs i.e., the mechanical torque T_m and the electrical torque T_e take on different values, a change in frequency ω is observable. This change is impacted by the inertia constant H that describes the amount of stored energy in the system and the rated frequency ω_0 of the network [10].

$$\frac{2H}{\omega_0}\frac{d\omega}{dt} = T_m - T_e \tag{1}$$

To avoid component failures, the rate of change of frequency (RoCoF) must not exceed system design parameters. It is the instantaneous change of frequency, occurring instantly after an incident, see Eq. 2.

$$RoCoF = \left.\frac{d\omega}{dt}\right|_{t=t_0^+} \tag{2}$$

Furthermore, the frequency nadir may not pass critical thresholds, otherwise network devices and units may disconnect from the system and aggravate the incident, see Eq. 3.

$$Nadir = \min\{\omega\} \text{ or } \max\{\omega\} \tag{3}$$

Frequency stability is the ability of a power system to maintain steady frequency following a severe system upset [11]. To ensure frequency stability, historically inertial response and reserves have been used to limit $RoCoF$ and $Nadir$ values. Inertial response is provided by the rotational mass in generation units that is electromagnetically coupled to the network frequency. The kinetic energy will be inherently passed as power to the network if $T_m - T_e \neq 0$. Reserve is activated based on frequency measurements. The fastest reserve category, Frequency Containment Reserve (FCR), responds through a droop control and is fully available within 30 seconds. There are two major strategies to overcome the expected shortage of frequency stabilization ahead of the activation of the fastest existing reserve product: First, a faster reserve, e.g., Fast Frequency Response (FFR). However, this does not mitigate initially high RoCoF values. Second, the use of GFM through sufficient units with this capability.

GFM capability can be implemented to any converter when newly designed. Yet, further design criteria e.g., the storage dimensioning of different technologies cause different GFM characteristics. The energy stored in the rotor blades of a wind park can be used for a short power boost, injecting power into the system. Photovoltaic plants can run in de-powered mode and the infeed may be instantly reduced or increased. HVDC links can make use of the energy stored in the capacitance of the setup [12]. Existing units must be refurbished with new control for an inherent response in order to be capable of making use of GFM to provide IFS.

III. RECENT DEVELOPMENTS

Countries facing challenges in frequency stabilization have chosen different approaches to keep system stability at required levels. In the following, an overview of comparably fast reserve products, as well as trends in network connection codes is presented.

A. Market-based solutions

One example is Ireland, where the Transmission System Operator (TSO) EirGrid procures FFR, which must be provided fully within two seconds and sustained for ten seconds after the start of an event. Additionally, a Synchronous Inertial Response is procured, where only kinetic energy of a centrally dispatched synchronous providing unit is contracted. This Synchronous Inertial Response must be provided for at least

15 seconds [13, 14]. Great Britain's TSO, the National Energy System Operator, is currently procuring a wide array of so-called frequency response services. One of these is Dynamic Containment with an activation speed of one second, and a duration of up to 30 minutes in both under and over frequency direction as a post-fault service, which is most similar to FFR [15]. Another example is Australia, where ten markets for frequency control ancillary services exist. Being split into upward and downward direction of provision, the fastest category are the very fast raise and the very fast lower, where units must have a response time of one second for a time frame of six seconds [16, 17]. Further examples for TSOs that procure FFR-like products include Hydro-Québec in Canada with a response speed of one second and a duration of nine seconds. In the United States, the independent system operators ERCOT and PJM implement mechanisms with a response time of 0.5 seconds and 2 seconds, respectively [18].

B. Network connection codes

The Agency for the Cooperation of Energy Regulators (ACER) proposes a revision of the Requirements for Generators (RfG) aimed at harmonization and detailing of standards and requirements for GFM units [19, 20]. The German energy regulator, Bundesnetzagentur, responsible for monitoring the TSOs, initiated procedure BK6-23-010 [21] to procure local frequency stability through a market-based procurement, revoking their previous exemption decision. Specifications and requirements for transparent, non-discriminatory, and market-oriented procurement are defined with the involvement of stakeholders. Meanwhile, the German Association for Electrical, Electronic & Information Technologies, VDE, published guidelines about requirements and verification processes as a technical basis for an incentive system to procure GFM capabilities [22]. Additionally, a classification of four categories and a differentiation between system support and GFM is suggested. GFM units of category 3 and 4 must at least be capable of providing their minimum (emulated/synthetic/virtual) inertia H_{min}. in a fictious island scenario without external support. System-supporting units i.e., category 1 and 2, are not required to do so [23].

TABLE I. DESIGN CHOICES FOR IFS

Design choice	**Advantage**	**Disadvantage**
Market auction	• Selection of the technologies with lowest provision cost. • Short auction periods allow heterogeneous IFS provision mix.	• Administration of the market requires ongoing expenses.
Network connection code	• Ensures (more than) enough IFS capability. • Standardization fosters reduced production cost. • Economics of scale	• Very slow response to over-capacity of IFS capability leads to inefficient resource allocation.
Regulated asset by the TSO	• Amount of investment can be chosen explicitly.	• Units can only be used for TSO tasks, i.e., no multi-use e.g. for load shifting. • Incentive for flawed IFS demand determination

IV. DESIGN CHOICES FOR IFS PROCUREMENT

The asset capability of IFS provision can be established through mandatory network connection codes, an incentivizing market-based procurement scheme or through regulated assets by the TSO. Table I compares the different design choices for IFS.

A. Network connection codes

The objective of network connection codes is to maintain fair conditions of competition, ensuring system security and integration of renewable energy sources (RES) while facilitating EU-wide trade in electricity [19]. They distinguish synchronous power-generating modules, power park modules and offshore power park modules. These categories induce different connection obligations. Renewable generation mostly belongs to the latter two categories. The network connection code on requirements for generators (RfG) must balance the above-mentioned targets to keep the entry barriers for renewable generation low while maintaining system security. Depending on the weighting of the different targets, network connection obligations can be redefined for example if the generation mix is shifting. In the upcoming years, the growing share of RES will make them a key technology. Thus, they are also expected to contribute increasingly to system security [24]. There is no clear legal distinction between system-friendly and system-disturbing behavior. In future, lacking IFS capability might be considered as system disturbing. In this case, the RfG would be adjusted to include more stringent minimum requirements to permit a connection. Yet, if many RES units are added under an altered network connection code, frequency stabilization may be shared among an increasing number of units. Then, the capability requirement of each unit may be lowered again to decrease the cost burden.

Network connection codes typically avoid a detailed distinction on technological level. Thus, mandatory installation of a capability will apply to a wide range of units. This is a possible cause for excessive costs or even stranded assets. Network connection codes can be adapted, but an update is a lengthy process, given the high number of stakeholders involved. Amendments of connection codes are scheduled on a regular basis. Thus, economic inefficiencies may arise over time or across different regions, due to delayed adaptations or too generic specifications neglecting differences in the generation mix of national energy systems.

B. Regulated assets by the TSO

Since the deregulation of electricity markets, the TSOs are not allowed to operate generation assets. This unbundling, introduced to prevent unfair competition on energy markets, also applies to the use of energy storage by TSOs. As an exception, TSOs may build and operate energy storage as a regulated asset if it is required for system security. These assets are referred to as fully integrated network components (FINC) and are used solely for secure network operation including e.g., reactive power, or black start capability, but not for balancing or congestion management [25]. In Germany, regulated assets are currently under planning e.g., so-called network boosters [26]. Yet, in all cases, a regulated asset can participate in less use cases from a system perspective than storage units owned by market participants. Therefore, it is unlikely that regulated assets are more efficient in the long-term than applying a tailored market design.

C. Market-based procurement

Many market segments have been introduced since the deregulation of the electricity industry. A common distinction is between spot markets where market clearing occurs shortly before delivery and future markets where products for upcoming years are traded. For IFS, the market is a monopsony, i.e., the TSO is the sole buyer of a certain quantity of IFS. The demand quantity may change with different network use cases and must be determined before market clearing. Methods for adequate dimensioning of IFS service demand are thereby still under research [27].

For markets, more tailored approaches may be feasible than for network connection codes, as network connection codes require more time when introduced or altered, given the high number of stakeholders that must be consulted for amendments. Key features of electricity market designs include the temporal and spatial granularity of the products. Well-functioning market segments are characterized by solid price signals and sufficient market liquidity to prevent market power. The market price provides incentives to stakeholders for participation and causes a self-selection of technologies with cheap provision costs as cheap technologies are rewarded with more net profit.

V. On Establishing IFS Procurement

To assess whether IFS should be procured with a market-based scheme, mandated through network connection codes or provided by regulated assets, a market simulation may be used. For such a simulation, a well-defined IFS product is necessary. Then, the results can be used to compare the provision cost through a market in relation to a standard provision via network connection codes. In the following, we discuss how an IFS product and the corresponding market may be designed.

Physical product properties: The IFS product can either be traded in energy or power units. Whereas on existing reserve markets power is traded, inertia estimation often considers energy. Before frequency determination, inherent power provision prevents high RoCoF values. Yet, sufficient inertial response is required to mitigate the system incident, until the reserve products are available. Thus, a combination is necessary. In the case of converter-based technologies, energy and power provision can be scaled independently. In contrast, synchronous machines cannot activate a pre-set amount of power during frequency events, but they only respond to the altered system state. Therefore, energy as a trading product is more inclusive. The additional requirements on a certain minimum power provision could be implemented as a characteristic curve, ensured through prequalification. IFS must be provided for low and high frequency contingencies. IFS might be designed as positive, negative, or bidirectional product that combines both directions. The overall positive and negative demand may not be identical, if both generation and load contingencies are considered for dimensioning. Also, converter units might only offer bidirectional IFS if they run in part-load operation as they must be able to inherently adapt their power output up- and downwards. If a positive and a negative product are introduced, participation is possible when running at full or zero power output. Thus, two different products – positive and negative – are in principle more tailored. Yet this requires in turn that the algorithms for (quasi-instantaneous) activation are also reacting asymmetrically to activation signals.

Temporal granularity: The duration of the market product should be short enough to account for variations in IFS demand that are a consequence of changing power system states, e.g. variable solar infeed potentials. Similarly to established spot markets, scarcities and the resulting prices may change in the course of a day. Hourly IFS products seem suitable to be tailored enough to reflect time-varying power system states and related variations in IFS demand, supply and scarcity. A corresponding market auction must be organized early enough to give room for unexpected events. If no market clearing is achieved, system operators must have sufficient time for fallback tasks. An auction on the previous day is a balance between forecast uncertainty and operational necessities. Furthermore, a market clearing in parallel to the spot auction prevents market power on sequential markets. On the other hand it requires the handling of complex bids, since spot energy and IFS offers may be interdependent (notably linked by the maximum converter capacity).

Regional granularity: In Europe, the reference case for FCR dimensioning is based on the loss of two of the largest power plants in the system. However, much larger power imbalances have arisen occasionally through system split events. In order to maintain the same level of system security, the separated systems must be kept within admissible frequency ranges through sufficient IFS. Thus, IFS should be provided by regionally distributed units. Considering system split events, such as on Nov 4th, 2006, or Jan 8th 2021, separation happened even within TSO regions, which is why a smaller regional granularity seems more suitable.

Pricing mechanism: Different pricing mechanisms are possible. In a pay-as-bid market, every supply obtains the price that was placed in the bid. In contrast, pay-as-cleared implies that all suppliers will obtain the price defined by the provision price of the last supplier. The latter pricing mechanism increases transparency, as only one market price must be communicated. Also, incentives to provide at cheap cost are prevalent. Similarly, investment in efficient technologies is incentivized, given that all suppliers obtain the same remuneration, regardless of their provision cost – implying that cheap provision results in higher net revenue.

VI. DISCUSSION

Introducing an IFS market-based product will have an influence on the existing energy system. Especially the bidding strategy of market participants on power and reserve markets may be affected. Furthermore, clearing times of auctions should be aligned to prevent market power. For system operation, the interaction of IFS, FFR and the existing reserve markets requires ongoing attention to identify and mitigate conflicting effects.

Comparing the different design choices for IFS, there are two procurement schemes that may yield economically efficient allocations of IFS capability. First, in a market-based short-term auction, generation resources that provide IFS at the lowest cost will clear the market. Even more, investment in these technologies is incentivized. Second, if the cost of provision is (almost) zero, mandatory provision through network connection codes may be a viable alternative to a market-based auction. Then, operational cost for running the marketplace and submitting bids may be avoided. Furthermore, standardization might keep provision costs for IFS low. From an economic perspective, regulated assets by the TSOs may only be an intermediate solution during a transition period. Regulation limits their use, serving for less purposes than the assets of market actors. Even though grid operators can implement them quicker than the other choices and they are suitable to prevent IFS shortages in the short run, they are prone to more expensive IFS procurement in the long run.

Whether a market-based auction or a provision through network connection codes should be fostered requires more research on the expected cost structure. Future research is especially required to assess the opportunity cost of IFS provision. A market simulation implementing the identified characteristics may indicate the time periods where the opportunity cost are greater than zero. Then, the result of the market simulation provides the cost-minimizing technology mix. Otherwise, if opportunity cost are (almost) zero, the efficient dispatch of IFS services is not a key priority. If moreover additional investment cost are low, there is no need for limiting the IFS capability to selected technologies and network connection codes are a solution with lower implementation cost.

VII. CONCLUSION

One challenge of fully decarbonized energy systems is to ensure frequency stabilization. This work reviews ongoing developments to facilitate frequency stability in systems with high shares of converter-based technologies. In conceptualizing novel or altered procurement schemes for frequency reserve, economic considerations are necessary to keep system costs affordable. This qualitative analysis concludes that incremental investment cost and the expected opportunity cost of IFS service provision determine the least-cost procurement design. Network-connection codes or a market-based solution are recommended. With the discussed procurement design choices, a simulation of market-based procurement can be realized and is ongoing research in the SysZell [28] project.

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