Frequency Provision with Low-Inertia Hybrid Power Plants: Identifying Gaps in the Standards

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Abstract—**Dramatic inertia reduction suffered in worldwide grids caused by the transition towards renewable and distributed generation, raises the risk of disturbances and blackouts due to frequency related issues. Subsequently, ENTSO-E has recently published several documents stating rules and recommendations regarding frequency support; such documents highlight the importance of developing new techniques in a grid dominated by generators with a power electronic-based interface. In fact, they are considered the first guidelines of an up-coming frequency control standard, which contemplates the possibility of having renewable and hybrid plants providing frequency stability as an ancillary service; but also proposes a new terminology and establishes the path to be followed in the following years. Therefore, the main goal of this paper is to assess the suitability of requirements provided in current standards.**

The paper critically reviews the last releases of ENTSO-E regarding frequency regulation and ancillary services provided by renewable and HyPP, identifies issues and points out gaps that have not been considered so far. Thereafter, a new approach aiming to avoid second and subsequent frequency dips after a large excursion is proposed.

I. INTRODUCTION

Recent sociopolitical tendency towards a more sustainable and reasonable use of the Earth's resources has motivated several agreements between countries and organisations aiming to change the way power is obtained and used; ultimately causing significant investments in green energy both from the public and private sectors. However, even though such transition is beneficial and must be continued, several authors like [1] have expressed their concern regarding frequency issues due to the fact that renewable based generation substitutes traditional Synchronous Generators (SG). Outcomes like time variant inertia and frequency instability are expected; which escalates blackout risk and the use-rate of load shedding. While SG provided grid stability naturally, power electronic interfaced generators are incapable since they are decoupled from the grid. Nevertheless, recent literature has proved how these generators can provide inertial support by applying special control approaches [2], [3].

Even though most renewable units are not synchronously coupled with the grid, there are several resources to be exploited in order to cover the stability needs of the network; i.e. synthetic inertia. Therefore, following such trend and due to the increasingly importance of improving the frequency response of systems with low levels of inertia, ENTSO-E recently released several documents [4], [5] where a future grid code stating the role of renewable plants in frequency related ancillary services starts to be shaped. Thus, it is now time to evaluate what is indeed needed to guarantee a safe frequency control with Renewable Energy Sources (RES).

The structure of this paper is as follows: Section II introduces the frequency behaviour of a power system; while Section III summarizes the key points of the new recommendations and regulations published by ENTSO-E. Then, Section IV presents a step by step approach for frequency recovery. Finally, Section V summarizes the obtained conclusions.

II. FREQUENCY BEHAVIOUR IN POWER SYSTEMS

A. Background and Definitions

The initial step of the analysis is equation 1. This equation expresses how an unbalance in the power generated and the load causes a frequency variation and how the speed (rate of change) of that variation is directly proportional to the unbalance while inversely to the inertia and the size of the system.

$$R = \frac{P_G - P_L}{2\,H_{eq}\,S_{eq}} f_n \tag{1}$$

Where R stands for Rate of Change of Frequency (ROCOF) [$\frac{\delta f}{\delta t}$], P_G, P_L, H, S, and f_n stand for power generated [W], power demand [W], equivalent inertia [s], size of the system [VA], and nominal frequency [Hz]. Subsequently, equations 2 to 5 define such variables.

$$P_G = \sum P_{G_i} \tag{2}$$

Where P_{G_i} represents the power generated by the generation unit i.

$$P_L = \sum P_{L_i} \tag{3}$$

Where P_{L_i} represents the power consumed by the load unit i.

$$H_{eq} = \frac{\sum H_i\,S_i}{\sum S_i} \tag{4}$$

Where H_i and S_i represent the inertia and apparent rated power of the generation unit i.

$$S_{eq} = \sum S_i \tag{5}$$

Where S_i represents the apparent rated power of the generation unit i.

The considered assumptions and limitations of this brief analysis are:

- The demand (P_L) is considered constant during the whole process, however there should be no problem if it varies in the vicinity of the expected value, thus not causing additional excursions.
- There is enough power available, which in renewable plants might not be the case. However, if the electric system is planned properly there should always be enough capacity.

B. Frequency recovery stages

The different frequency recovery stages are defined in [4]. Then, Figure 1 presents the typical frequency response of any power system after a major power imbalance; where A represents the event starting point, B is the Nadir, or lowest value reached by the frequency, C represents the end of one of the control stages, and point D sets the steady state frequency. In the figure, three main actuation phases or stages can be distinguished according to ENTSO-E terminology: Fast Frequency Response (FFR), Frequency Containment Reserve (FCR), and Frequency Restoration Reserve (FRR) [4]. Table I presents a summary of control stages defined in frequency control and their relation with the traditional frequency control definitions; that is Inertial Response (IR), Primary Frequency Response (PFR) and Secondary Frequency Response (SFR).

Regarding the specific actuations to be held in each stage, [6] covers FCR, FRR and presents RR for the first time. Such RR is used to support FRR if additional system imbalances would arise during the recovery. Despite of the fact that there is no mention of FFR in such document, it does present the concept of Synthetic Inertia, which is closely related; [7] elaborates more about the need of inertia provision. Then, finally, [5] establishes that the system should be able to withstand a 40 % load imbalance.

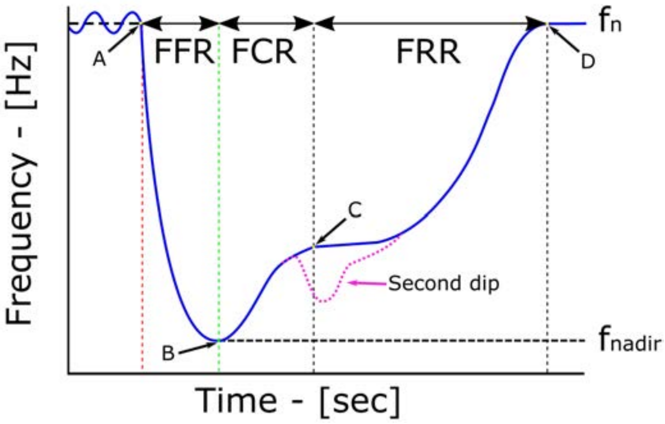

Fig. 1: Typical frequency response [3]

TABLE I: Control Phase Summary

Stage	FFR	FCR	FRR
Interval	A-B	B-C	C-D
Origin	Virtual inertia	Reservoir	Generation adjustment
Similar To	IR	PFR	SFR

It should be pointed out that, IR is a natural uncontrollable response of the SG while, FFR; is a controllable non-spontaneous reaction of the generators in a grid; which is limited by mechanical and electrical control boundaries, and available power. Also, Figure 1 is showing a second dip; which is a frequency drop occurred after IR or FFR and it is caused by incorrect frequency recovery strategies rather than a fault or an event in the grid. The main objective of any frequency recovery strategy is to return the frequency to its nominal value after the occurrence of an event, without any subsequent frequency dip like shown by the red line. The importance of the second dip is related to load shedding schemes, that will be unnecessarily activated due to the way in which protective relays are configured. Those devices will detect the whole time spawn from the event occurrence to the -th dip as one long fault [3]+.

III. NEW ENTSO-E REGULATIONS

The documents recently published by ENTSO-E state rules and recommendations regarding frequency support; highlighting the importance of developing new techniques in a grid dominated by generators with a power electronic-based interface.

The guideline on electricity transmission is [8], where there is no mention of FFR; relaying entirely on IR in order to keep the frequency stable. Regarding FCR, the target is to reduce to zero the frequency restoration error in a specific control area with a maximum deadband of 10 mHz. The main points of FCR in this document are:

- FCR has to be annually determined in order to ensure enough capacity.
- the reserve has to be at least as big as the reference incident (the worst one recorded) and never less than 3 GW.
- its activation should not be artificially delayed, beginning as soon as possible after the frequency deviation.
- if the deviation is equal or higher than 200 mHz at least 50 % of the full capacity should be delivered in less than 15 seconds, and 100 % in less than 30 seconds.

Again in [8], the main characteristics of FRR are covered:

- its determination is based in at least one full year period ending not earlier than 6 months before the calculation date
- it is triggered by the TSO when needed, it doesn't start after a specific time after the event.
- The delay after the trigger must be less than 30 seconds.

Summarizing, such regulations and guidelines still make use of IR to initially stop the ROCOF after a major event, even though they are concern about the insufficient inertia present in the grids. Therefore, FFR will foreseeable be included in a future revision of such standards. Subsequently, FCR and FRR are basically the same as the traditional PFR and SFR. This approach seems to work fine during regular operation, account just for minor oscillations in generation and load. However, it is insufficient in large frequency excursions like the loss of a major generation unit, specially when considering the interest in avoiding the second dip [7].

Despite of the fact the old approach is sufficient to ensure regular operation; there is a clear need for an adaptation of frequency restoration techniques after large excursions, since smooth recovery is not guaranteed. Also, the standards establish what to do, but not how; traditionally there was basically one kind of generator (synchronous), but nowadays many different technologies coexist; that factor should also be reflected in the standards.

IV. PROPOSED APPROACH

As aforementioned, ENTSO-E recommendations work fine during regular operation, thus, the proposed method targets only large frequency excursions; ensuring a smooth frequency recovery after a large excursion.

A. Defining Large Frequency Excursions

Frequency events are defined in [6] as frequency deviation of $50 \pm 0,2Hz$, although is not considered worth responding to it until it overpasses a threshold of $50 \pm 0,5Hz$. This approach works well in highly inertial systems since the IR will take care of most deviations without activating any control action. However, it presents a number of problems in systems with low IR capacity since the system will not only react less to the event, but also, any implemented controlled action will be unnecessarily delayed. For this reason, in [3] the possibility of combining frequency and ROCOF as detection system for large excursions was proposed and successfully tested. For the sake of this paper, large excursion is defined as a sudden power unbalanced that the system will not be able to clear with IR alone.

B. Event - N-1 Contingency

The considered event is a sudden loss of generation, this might be caused by the tripping of a large generation unit. It corresponds to point A in Figure 1; such event is defined as equation 6.

$$P'_G = P_G - P_G^{Tripp} \tag{6}$$

Where P'_G is the new active power generated in the system after the tripping, while P_G^{Tripp} is the active power injected by the tripped unit which responds to equation 7.

$$0 < P_G^{Tripp} < P_G \tag{7}$$

Then, equation 1 can be updated as:

$$R = \frac{P'_G - P_L}{2\,H_{eq}\,S_{eq}} f_n = \frac{P_G - P_G^{Tripp} - P_L}{2\,H_{eq}\,S_{eq}} f_n \tag{8}$$

In other terms, the frequency will drop after the lose of generation and vice versa.

$$\Delta R = \frac{\Delta P_G - P_L}{2\,H_{eq}\,S_{eq}} f_n \tag{9}$$

$$\Delta R < 0 \;\rightarrow\; f \downdownarrows \tag{10}$$

After the event, the frequency will drop, then the first stage of the frequency recovery (FFR) will be triggered with the objective of stop the frequency drop.

C. Stage 1 - Fast Frequency Response

FFR, traditionally IR, is related to the inertial response of the synchronous generators in the system. While IR was a natural uncontrollable response, FFR is a controllable non-spontaneous reaction of the generators in a grid. Thus, due to the amount of converter-based generation units; this stage has been renamed as FFR.

This stage starts once the event is detected (shortly after point A) and stops once the frequency has reached a fixed value, i.e. $(ROCOF = 0)$. It should be noted that the new frequency value reached after FFR is different from the starting point. In Figure 1 such point is noted with letter B and corresponds to the Nadir.

After FFR activation it is necessary to redefine Power injected as:

$$P''_G(t) = P'_G + P_G^{FFR}(t) \tag{11}$$

Where $P''_G(t)$ is the new active power generated in the system after the FFR stage starts, while $P_G^{FFR}(t)$ is the active power injected by the FFR stage. It should be noted that this quantities are time dependent. This injection is summation of two different values, as presented in equation 12. Such definition of FFR is not yet on any standard, however [2] has proven its feasibility and suitability.

$$P_{FFR} = P_{Droop}^{FFR} + P_{df/dt}^{FFR} \tag{12}$$

Where P_{Droop}^{FFR} and $P_{df/dt}^{FFR}$ correspond to the Droop and ROCOF based injections of the FFR stage as presented in [2]. Subsequently, P_{FFR} will gradually increase until matching P_G^{Tripp}; thus equation 1 can be updated as:

$$R = \frac{P''_G - P_L}{2\,H_{eq}\,S_{eq}} f_n = \frac{P'_G + P_G^{FFR} - P_L}{2\,H_{eq}\,S_{eq}} f_n \tag{13}$$

Then, combining it with equation 8 the Nadir point can be obtained as the instant when power generated and consumed become equal again as presented in equation 14. Then, Figure 2 presents the expected frequency, ROCOF and $P''_G(t)$ evolution if only FFR is implemented as according to equation 13. It should be noted that the event and the Nadir times are highlighted with a red and a green vertical line respectively. Therefore, it can be concluded that it is necessary to add subsequent stages in order to recover the frequency.

$$R = \frac{P_G + P_G^{FFR} - P_G^{Tripp} - P_L}{2\,H_{eq}\,S_{eq}} f_n = \frac{0}{2\,H_{eq}\,S_{eq}} f_n = 0 \tag{14}$$

Provided that:

$$P_G^{Tripp} = P_G^{FFR} \neq 0 \tag{15}$$

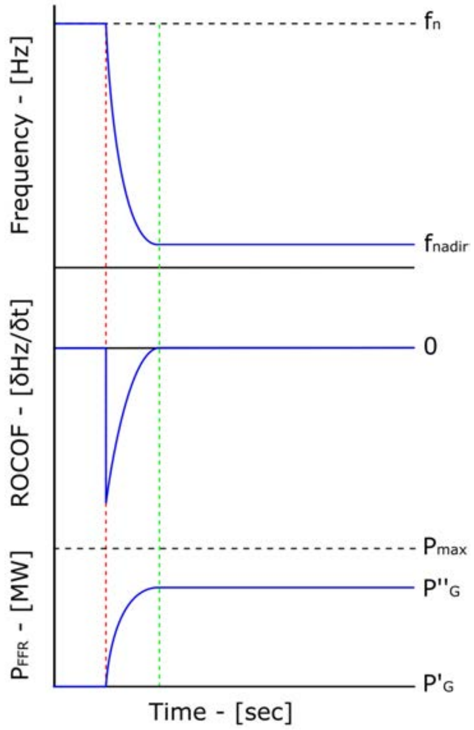

Fig. 2: Frequency response implementing only FFR.

D. Transition between stage 1 and 2 - Nadir Point

Before analysing the recovery, it is important to understand what is happening in the Nadir point and how this transition should be carried. Again, it is important to state the non-existence of literature covering such topic.

The basic idea in the Nadir is that, the upcoming FCR has to pick up the recovery from the last FRR active power value and keep increasing the injection until the frequency is restored. In other words, if equation 16 is not met; then $R < 0$ which will unavoidably cause a second dip.

$$P_{FCR}^{t0} \geq P_{FFR}^{tn} \tag{16}$$

Where P_{FCR}^{t0} and P_{FFR}^{tn} are the power injected in the initial instant of FCR and the last instant of FFR. In practice, if $P_{FCR}^{t0} = P_{FFR}^{tn}$ then $R = 0$, then the recovery can continue.

E. Stage 2 - Frequency Containment Reserve

Once the starting point of the Stage 2 is set, the objective is to gradually increase power injection in order to increase the frequency and then reduce it again to avoid overpassing the nominal value. In this stage, the speed of the recovery is not critical, in fact it is more important to ensure a smooth recovery. Note that it is necessary to redefine Power injected as:

$$P_G'''(t) = P_G'' + P_G^{FCR}(t) \tag{17}$$

In the standards, FCR is performed with a droop characteristic (defined by equation 18) with values ranging from 1 to 12; as the one presented in Figure 3, it should be noted how it presents a dead band in order to avoid over-actuation. However this method presents disadvantages:

- Does not ensure the necessary transition explained in Section IV-D.
- Does not consider the speed at which the frequency is being modified (ROCOF), thus being prone to oscillations.
- The deadband prevents a complete frequency recovery.

$$Droop = -100 \frac{\frac{f_{meas}-f_n}{f_n}}{\frac{P_G-P_n}{P_n}} \tag{18}$$

Where Droop is a constant ranging from 1 to 12, f_{meas} is the measured frequency, f_n the nominal frequency, while P_G and P_n are the instantaneous and nominal active power injections of the system (or generation unit) respectively.

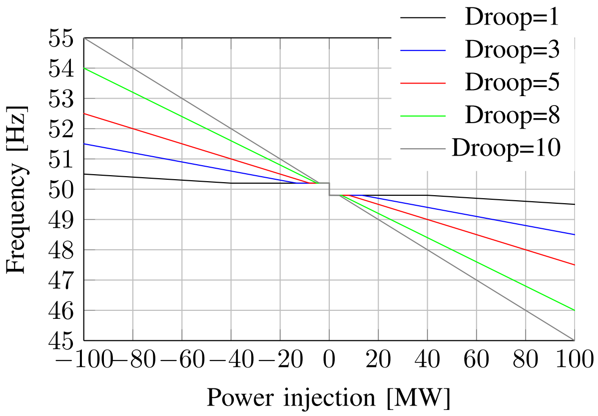

Fig. 3: FCR characteristic for different droop values.

In this proposed method, FCR acts depending on the actual frequency excursion and the dynamics of the system rather than with a rule of thumb as presented in the standards. Ideally, the overall system response is presented in Figure 4, where the frequency, ROCOF and active power injection are presented for the duration of the contingency. Again, the event and Nadir times are highlighted with a red and a green vertical line respectively.

There are two possibilities to be investigated regarding the practical implementation of this control method. On the one hand, a Nadir dependent droop (initialized as $P_{FCR}^{t0} = P_{FFR}^{tn}$) which will apply a direct relationship between the Droop value and the Nadir; i.e. if the Nadir point is reached in 49.4 Hz, the droop will be 8 while if it is reached at 49.2 Hz, it will be 3. In this way, a higher sudden generation increased is requested during more dangerous events. On the other hand, an alternative could be a dynamic droop. In this system, the droop rate will be calculated based on frequency and ROCOF; this will allow to have a fast recovery in the beginning without dips and then reduce the power injection smoothly until the recovery is completed. Additionally, this would also allow every-plant to support independently the frequency recovery since it will be based on local values; there won't be a need for an external controller to establish set-points and there will be no risk for hunting effect. In fact, with the dynamic droop, a third stage of frequency

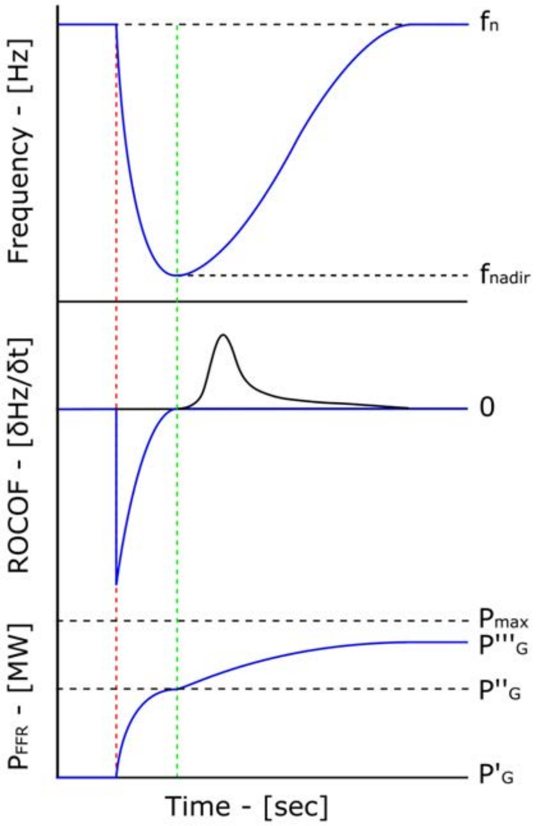

Fig. 4: Expected Response of the proposed method.

recovery seems unnecessary, unless additional imbalances are considered on top of the first one; in such case, the inclusion of RR should be further investigated. Finally, it should be pointed out that the Nadir dependent droop has the advantage of being easier to implement, while the dynamic droop approach is more accurate.

V. CONCLUSIONS

In this document, current standards regarding frequency recovery have been reviewed and criticized, point out wholes in their approach. Subsequently, the mathematical background defining the frequency recovery of any electric system has been presented leading to the definition of a new approach in frequency recovery. The proposed method considers the new characteristics of a electric grid dominated by generation units coupled to the network with power electronics and renewable energy.

By following this new method second and subsequent dips are avoided. Also, since the method relies on local measurements, the different local frequency variations are considered. However, it is necessary to validate the method with simulations. More research is needed in order to establish the real characteristic of the FCR stage.

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