Technical Annex of the methodology for performing the probabilistic dimensioning of FCR in CE synchronous area according to Article 153(2) of Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation

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1 Acronyms and references

ACE	Area Control Error
CE	Continental Europe
LER	FCR providing units or groups with limited energy reservoir
FCR	Frequency Containment Reserve
FCP	Frequency Containment Process
FRR	Frequency Restoration Reserve
FRP	Frequency Restoration Process
FSM	Frequency Sensitive Mode
Non-LER	FCR providing units or groups without limited energy reservoir
NP RES	Non Programmable Renewable Energy Sources
RES	Renewable Energy Sources
SO GL	System Operation Guideline
SA	Synchronous Area
$T_{min\ LER}$	As of triggering the alert state and during the alert state, time for which each FCR provider shall ensure that its FCR providing units with limited energy reservoirs are able to fully activate FCR continuously.
FAT	Full Activation Time of FRR
ROCOF	Rate of Change of Frequency

[1] COMMISSION REGULATION (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation.

[2] ENTSO-E, SPD, "Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe", 2016.

[3] ENTSO-E, SPD – Inertia TF, "Inertia and Rate of Change of Frequency (RoCoF)", 2020.

[4] ENTSO-E, "ENTSO-E HVDC Utilization and Unavailability Statistics 2021", 2022.

2 Methodology for probabilistic approach for FCR dimensioning

2.1 Overview and description of the methodology

The methodology to perform the FCR probabilistic dimensioning required in the Continental Europe Synchronous Area is based on a probabilistic model which randomly combines the most important source of power imbalance in the system and simulate the resulting frequency deviation.

The model works on a large set of simulated years, in order to reach probabilistic significant results.

According to Article 153(2)(c) of SO GL, the probabilistic approach to FCR dimensioning shall be aimed at reducing the probability of insufficient FCR to below or equal to once in 20 years.

Namely, whenever a power imbalance exceeds the available FCR, the FCR is considered insufficient. In terms of frequency deviation, such condition results in a steady state frequency deviation larger than the Maximum Steady State Frequency Deviation (at which FCR shall be fully deployed).

Moreover, since the available FCR impacts also the frequency transient following a sudden change in power imbalance. “insufficient FCR” conditions are also those conditions where the frequency dynamic performances are severely degraded. , i.e. those conditions whenthe frequency exceeds specific thresolds in terms of Δf peak or ROCOF.

The purpose of the model is thus to determine the minimum amount of FCR which allows to ensure that the insufficient FCR conditions (i.e., a Critical Conditions) occur not more often than once in 20 years.

A Critical Condition is a serie of minutes spaced each other not more than a parametrical number of minutes and meeting one or more of following criteria:

a. The absolute value of Steady State Frequency Deviation (SSΔf) as simulated by the Probabilistic Simulation Model exceeds the steady state maximum frequency deviation (200 mHz fro CE)
b. The absolute value of frequency peak reached during a transient exceeds the admissible tresholds .
c. The absolute value of ROCOF exceeds the Maximum Initial ROCOF.

Maximum Transient Frequency Deviation and Maximum Initial ROCOF are parameters defined by TSOs and made publicly available before the execution of the methodology.

The model starts with the current deterministic FCR. The model then iterates increasing step by step the FCR until the number of Critical Conditions in the simulated frequency deviation is such that they occur not more often than once in 20 years.

The model takes into account the potential presence of LER (Limited Energy Reservoir FCR providers) in the calculation of the results.

- The Probabilistic Simulation Model shall take into account:Outages on generation plants and HVDC connections. Details on how the power imbalance is calculated are provided in Section 2.4.
- Power imbalance associated with Deterministic Frequency Deviations (DFDs). Details on how the DFDs are calculated are provided in Section 2.2.
- Power imbalance associated with Long-Lasting Frequency Deviations (LLFDs). Details on how the LLFDs are calculated are provided in Section 2.3.

DFDs and LLFDs are calculated starting from historical data of frequency deviations while the power imbalances due to outages are derived from outages statistics.

An overall power imbalance is randomly generated from these three different sources of disturbance. Such power disturbance is used to calculate simulated frequency deviation trends which are then analysed to verify whether they fulfill the minimum acceptance criteria.

The whole model operates with a time granularity of one minute. Hence the power input power imbalance as well as the simulated frequency deviations are trends with 525600 minutes a year (leap-year presence is neglected).

The overview of the process is shown in the following Figure 1.

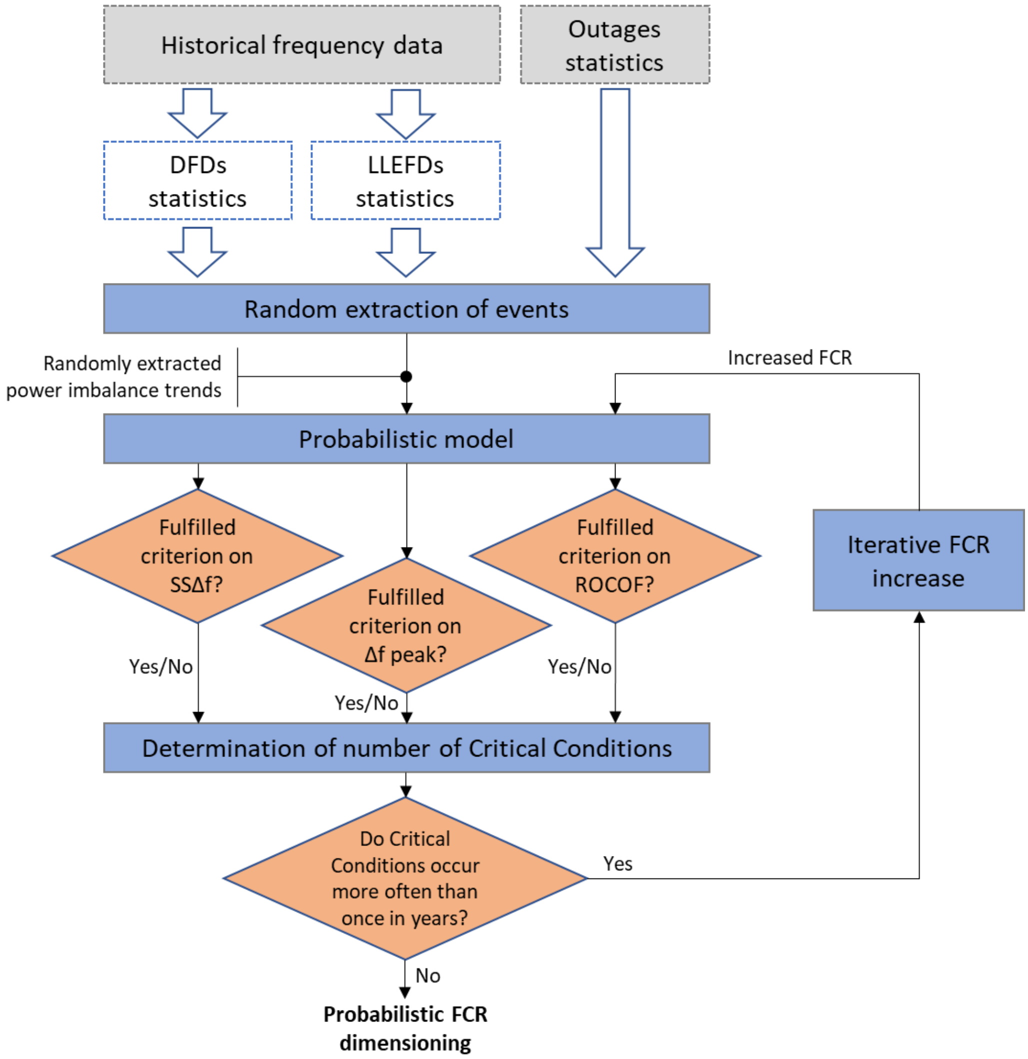

Figure 1: General overview of the model adopted for the probabilistic approach for FCR dimensioning

Figure 2 provides a more detailed depiction of how the input statistics (frequency, outages) are exploited.

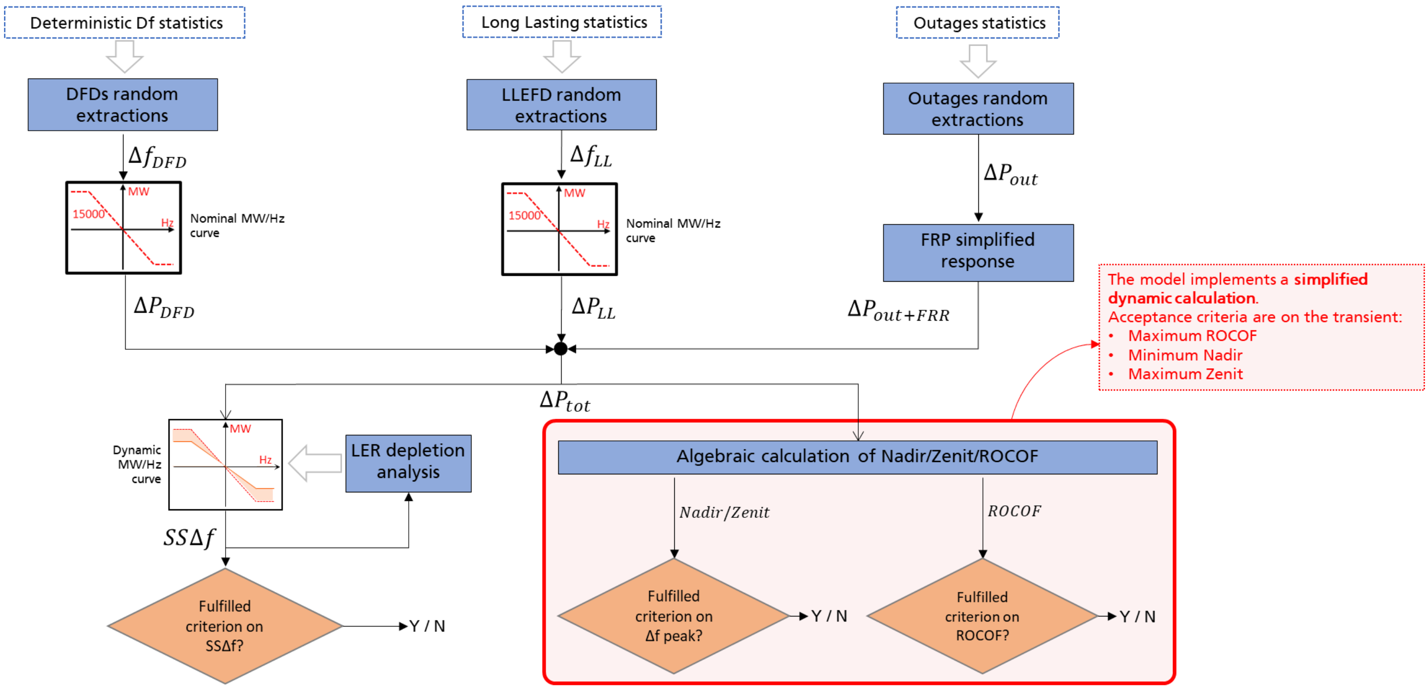

Figure 2: Detailed overview of the model adopted for the probabilistic approach for FCR dimensioning

2.2 Functionality for DFDs statistics and DFDs random extractions

DFDs are market-induced frequency deviations which regularly occur around the change of the market time unit (usually the change of hour).

In the model, the statistic of DFDs are directly calculated from the historical frequency trends with 1-minute granularity. The model extracts the frequency around the change of hour: are considered as DFDs all the frequency samples in a minutes range around the minute 0 (DFD interval).

For each simulated year, this functionality is aimed at calculating a trend of the frequency deviation due to DFDs.
This trend is equal to 0 for all the minutes m which do not belong to the DFD interval. The minutes m belonging to the DFD interval are taken from the input historical frequency trends.

DFDs are randomly selected for the input of the model, looking at homologous days in past years. For example the DFDs to be assigned to 1st January of a simulated year are directly taken from the DFDs which actually occurred in the system during the 1st January of a randomly selected past year (e.g. 2018). This mechanism allows to keep the daily pattern of occurrence for DFDs: for example, the DFDs occurring around 6 am are taken from the same hour in the same day of another year.

The random choice of the year is biased towards most recent years. The probability of the past year y is indeed calculated with the following formula:

$$p_y = \frac{1}{N_{years}} e^{-\frac{y-y_{last}}{N_{years}}}$$

Where:

y_{last}	is the most recent year for which data are available;
N_{years}	is the number of years for which historical trends are available.

The functionality results in a frequency trends composed by randomly extracted DFDs.

2.3 Functionality for LLFDs statistics and LLFDs random extractions

For the purpose of FCR dimensioning, the definition of long-lasting frequency deviations (LLFDs) is a “condition with an average steady state frequency deviation larger than a share of the Standard Frequency Range over a period longer than the Time To Restore Frequency”.

The tool scans the frequency trends acquired as input to detect all such conditions.
The scan operates following these rules:

- A moving average (with a width equal to Time to Restore Frequency) scans the data of a whole year.
- If the moving average frequency deviation exceeds a threshold equal to a share of the Standard Frequency Range, a LLFD is detected.
- The LLFD length is calculated looking at its average frequency. The LLFD lasts as long as its average frequency exceeds a share of the Standard Frequency Range. This average is calculated from the beginning of the LLFD).

A list of all the detected LLFDs is created. Each LLFD is associated with the following information:

- Year of occurrence;
- Minutes in which it started;
- Duration;
- Frequency trend (vector of df characterizing the event)

These statistics are than exploited to generate a random extraction of LLFDs to be used as input by the model.

The procedure iterates on all the minutes of the year, asfollows:

1. It decides whether or not a LLFD starts at minute m.
   This choice depends on the probability that a LLFD starts at the generic minute m of a day (e.g., at 02.15 PM). The latter probability is equal to the ratio between the number of LLFD starting in the minute m (in the whole frequency dataset) and the number of days in the frequency dataset ($365 * N_{years}$).
   If no LLFD occurrence is extracted, the procedure proceeds analysing the following minute (m+1).
   If a LLFD occurrence is extracted, the procedure proceeds at the step 2.
2. The year y from which to select a LLFD starting at minute m is randomly extracted. For this the following probability is used:
$$p_{m,y} = \frac{1}{N_{m,years}} e^{-\frac{y-y_{last}}{N_{m,years}}}$$
   Where $N_{m,years}$ is the number of years for which at least one LLFD starting at minute *m* has been detected and y_{last} is the most recent year for which data are available;
3. The specific LLFD to be used is then chosen from the set of all LLFDs started at minute m and occurred in the year y (chosen in the step 2). The random choice of the specific LLFD to be used is based on an uniform distribution: all LLFDs in the set have the same probability to be chosen.
4. The selected LLFD is assigned to the trend. If the LLFD lasts for k minutes, the LLFD frequency trend is assigned to the interval between minute m and minute m+k-1.
5. The procedure returns to step 1 for minute m+k.

The functionality results in a frequency trends composed by randomly extracted LLFDs.

2.4 Functionality of outages random extractions and calculation of associated power imbalances

The outages are provided as input already in a statistical form: each potential event is associated with its:

- power loss: power change as of the event occurs;
- probability of occurrence: average number of events in a year.

The random extraction of outages uses as input the list of possible events

The extraction operates cycling on all the minutes of the year. For each minute m, all the possible events are tested to verify whether they occur or not.
For each possible event v, a random value in [0, 1] is generated and it's compared with the probability that the event occurs in the minute ($p_{v,m}$):

$$p_{v,m} = 1 - e^{-\frac{FR}{365*24*60}}$$

Where FR: $Failure\ Rate$ is the average number of occurrence in a year for a specific outage.

If the random generated value is below $p_{v,m}$ the outage occurs. It means that the system must cope with the power imbalance associated with the event.

The total amount of power imbalance in each minute is equal to the sum of the power imbalances of all the events which are extracted in that minute.

The result of the calculation is a yearly power imbalance trend due to extracted outages.

FRR effects are applied to such calculated power imbalance yearly trend. The FRR is modelled as a simplified 1st order dynamic system. The power imbalances are brought to zero by FRR with a time constant equal to 1/3 of the FRR FAT.
After roughly 3 time constants the transient is ended, this condition simulates the restoring effects of FRR in balancing the power imbalance due to outages within FRR FAT.
The following Figure 3 shows an example of the FRR effects on the power imbalances due to outages.

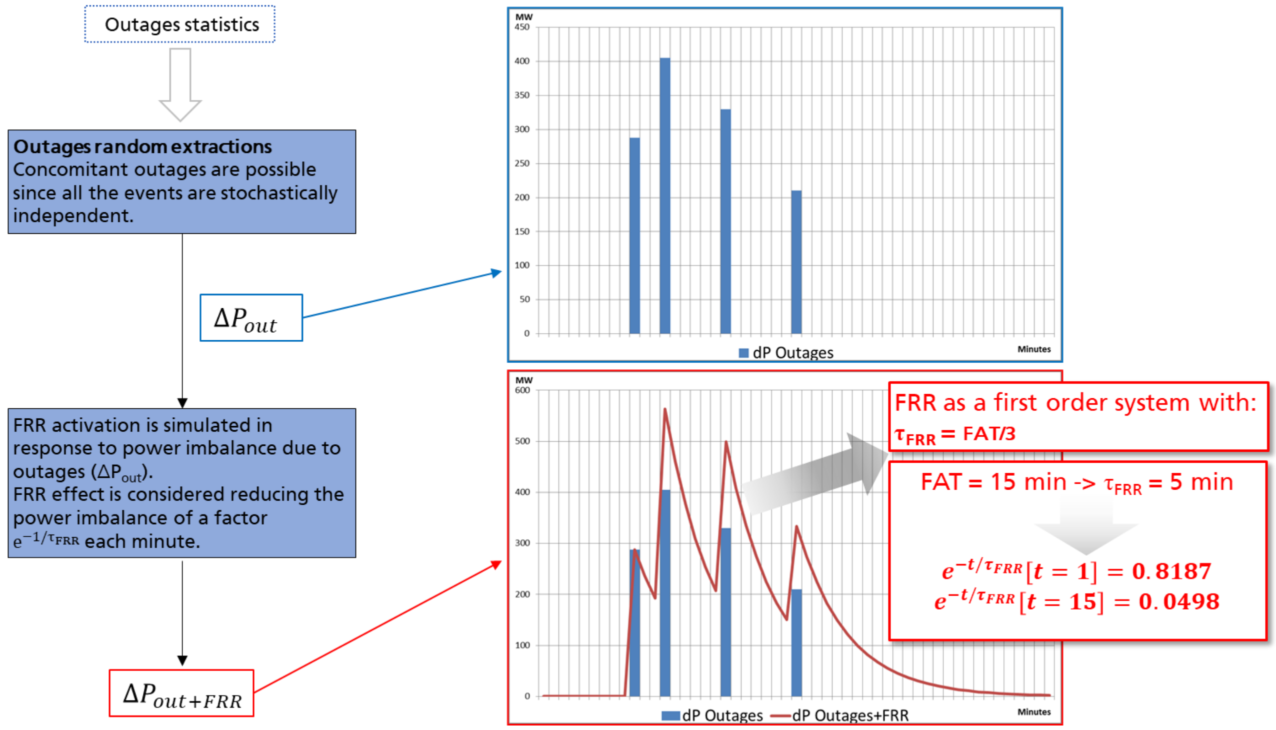

Figure 3: Example of FRR effects on power imbalance due to outages (15 min FAT is merely illustrative)

The functionality results thus in power imbalance trends due to outages and consequenct FRR activation.

2.5 Functionality of combination of extracted DFDs, LLFDs and outages to generate global power imbalance trends

The combination of the input due to different sources takes place in terms of power imbalance: the power imbalance due to outages is combined with the power imbalance corresponding to DFDs and LLFDs.

In order to convert the frequency deviation trends into equivalent yearly power imbalance trends, a converting module is used. The module operates the conversion using a MW/Hz curve (given as input). In other words, the frequency deviations due to DFDs and LLFDs are converted into power imbalances assuming the conversion factor which was in place at the moment of their real occurrence. Such converting factor is the MW/Hz dependency with a FCR equal to the value present in the year the data are referred to (e.g., 3000 MW for years up to 2024).. Such MW/Hz dependency doesn’t change during the iteration since it is related to historical data trends.

The global power imbalance is obtained by summing the three power imbalances (due to LLFDs, DFDs, and outages).

To avoid overlaps between DFDs and LLFDs the priority is given to LLFDs. LLFDs and DFDs are not summed each other, but - on each minute - the presence of a LLFD overrides the presence of a DFDs.

2.6 Model to calculate the steady state frequency deviation in every minute.

This functionality progressively simulates system operation (in terms of frequency control) over the 525600 minutes of a year.

For each minute m it calculates the stady state simulated frequency deviation ($SS\Delta f_m$) considering as input:

- The global power imbalance: ΔP_m
- current regulating energy: $reg.en._m$

The regulating energy depends on the FCR amount in the current interation and on the possible exhaustion of LER present in the FCR provision.

The output of the functionality is the simulated steady state frequency deviation trend ($SS\Delta f$).

Such variable is modelled through a MW/Hz curve as shown in the example of Figure 4.

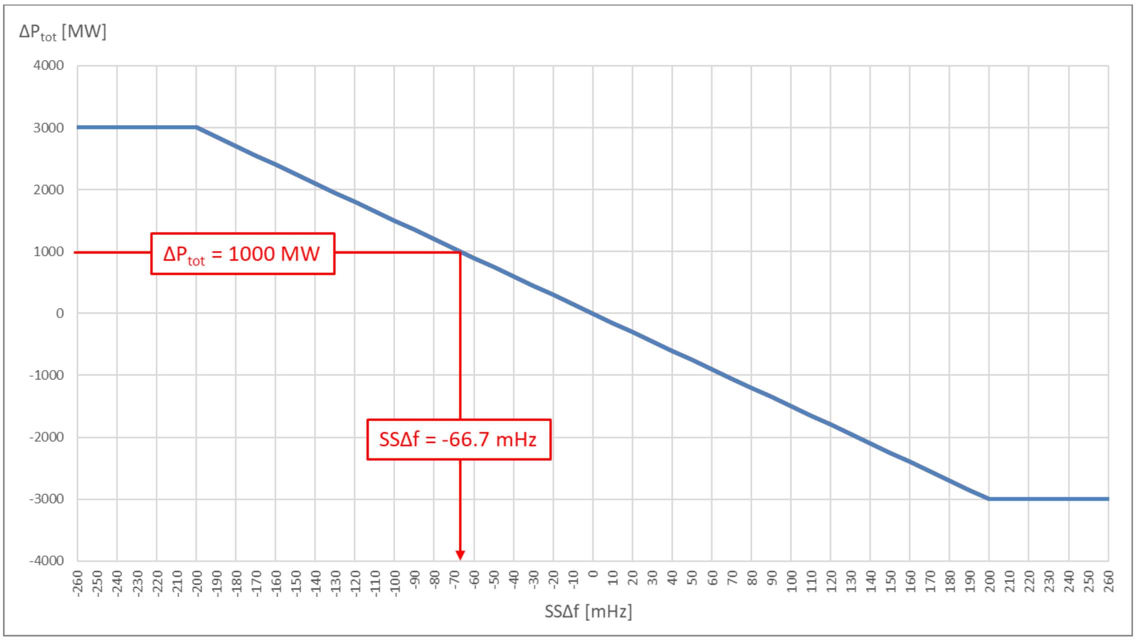

Figure 4: Example of using a MW/Hz curve of 3000 MW/Hz to calculate SSΔf from ΔP_{tot}

A change in the regulating energy ($reg.en._m$) leads to a different frequency deviation, starting from the same power imbalance.

The standard regulating energy depends on the procured FCR. For instance, if in the current iteration a condition with FCR = 3000 MW is considered, the standard regulating energy ($reg.en_{standard}$) is equal to 15000 MW/Hz (i.e., 3000 MW of FCR with full activation at 0.2 Hz).

Should a LER depletion be detected, the regulating energy ($reg.en._m$) decreases and the modelled curve has to be rescaled.

When LER reservoirs are depleted, their FCR contribution is indeed considered as instantaneously lost (they cannot provide anymore upward/downward regulation power).
Only the non-LER providers are still available to regulate the system. Given an input power imbalance, the resulting frequency deviation is thus greater than in the situation with all the LER available.

This condition is modelled with a reduction of regulating energy (i.e., a rescale of the MW/Hz curve) equal to the proportion of FCR lost due to the LER depletion. This proportion is the LER share.

For instance, if the LER share is 50%, once the LER are depleted the regulating energy is reduced by a factor 2 (the MW/Hz is rescaled by a factor 2). It means that the frequency deviation associated with a power imbalance is doubled if compared to the standard condition.
The following Figure 5 shows the reduction in such example.

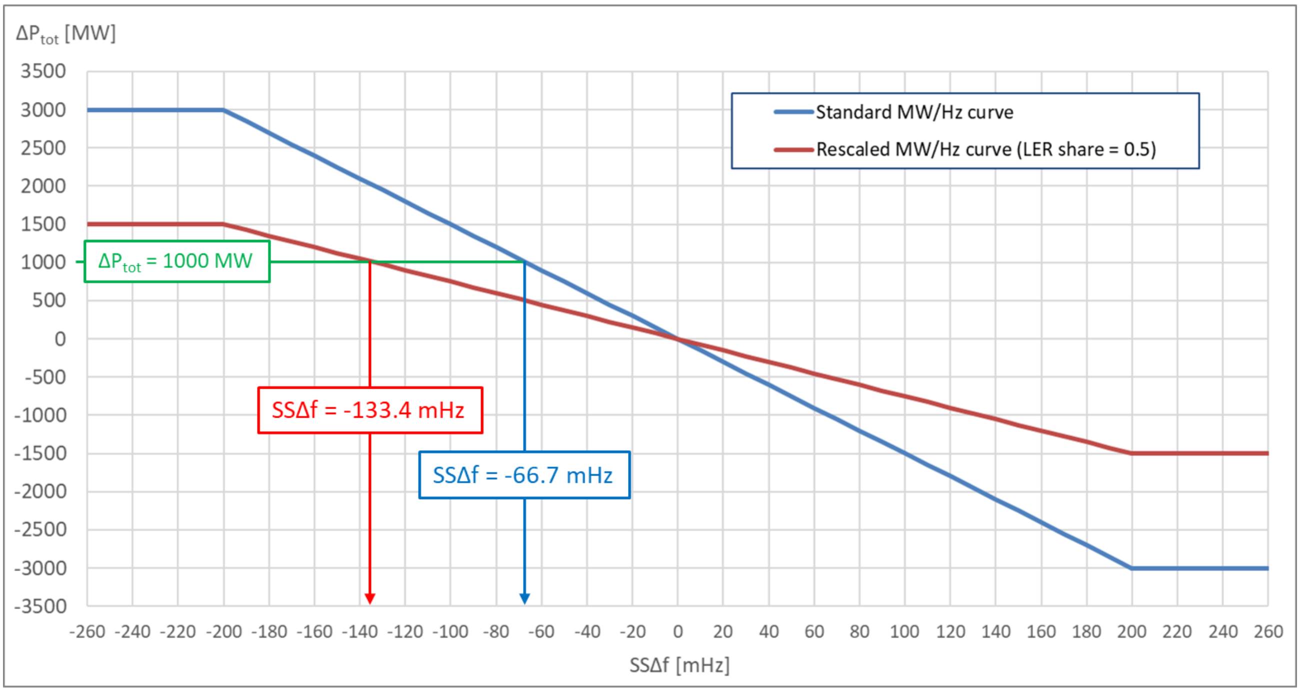

Figure 5: Example of rescale of MW/Hz curve by a factor 2

The model update at each minute m the current regulating energy ($reg.en._m$). The formula is:

$$reg.en._m = \begin{cases} reg.en_{standard} \cdot (1 - LER\ share), & if\ LER\ are\ depleted \\ reg.en._{standard}\,, & if\ LER\ are\ not\ depleted \end{cases} \quad (1)$$

To check whether the LER are depleted or not, the energy content of LER reservoir is calculated in each minute.
The Figure 6 schematically shows the process by which the regulating energy is rescaled as a consequence of the a LER depletion.

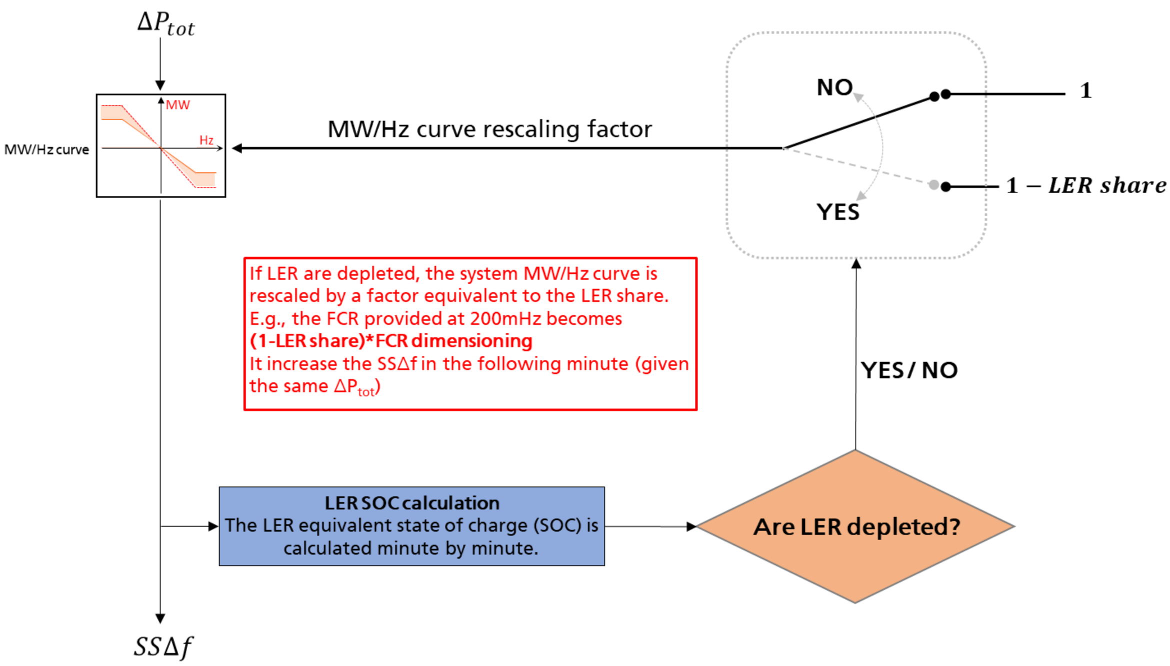

Figure 6: Schematic procedure for rescaling MW/Hz curve as a result of LER depletion

The combined effects of the recharging strategy and of the simulated frequency deviation can lead the LER to recover from a depletion condition. As this occurs, the regulating energy returns to its standard condition (e.g., 15000 MW/Hz if FCR = 3000 MW).

The LER are considered without energy limitations while frequency remains inside the Standard Frequency Range.

If a continuous exceeding of the Standard Frequency Range includes the triggering of an alert state[1], the activated energy and the residual energy in the reservoir is calculated from the triggering of the alert state..

LER deplete as their reservoir reaches the maximum or minimum energy level. The capacity of the reservoir depends on the minimum activation time period the LER are subject to.

2.7 Model to calculate the dynamics of the frequency deviation in each minute.

The characteristics of the frequency during a transient - such as the frequency peak (nadir or zenit) and the ROCOF – need to be considered for the FCR dimensioning process (Figure 8).

[1] An alert state is triggered if at least one of the following conditions occurs:

- The absolute value of simulated steady state frequency deviation exceeds for 5 consecutive minutes half of the Maximum Steady State Frequency Deviation.
- The absolute value of simulated steady state frequency deviation exceeds for 15 consecutive minutes the Standard Frequency Range.

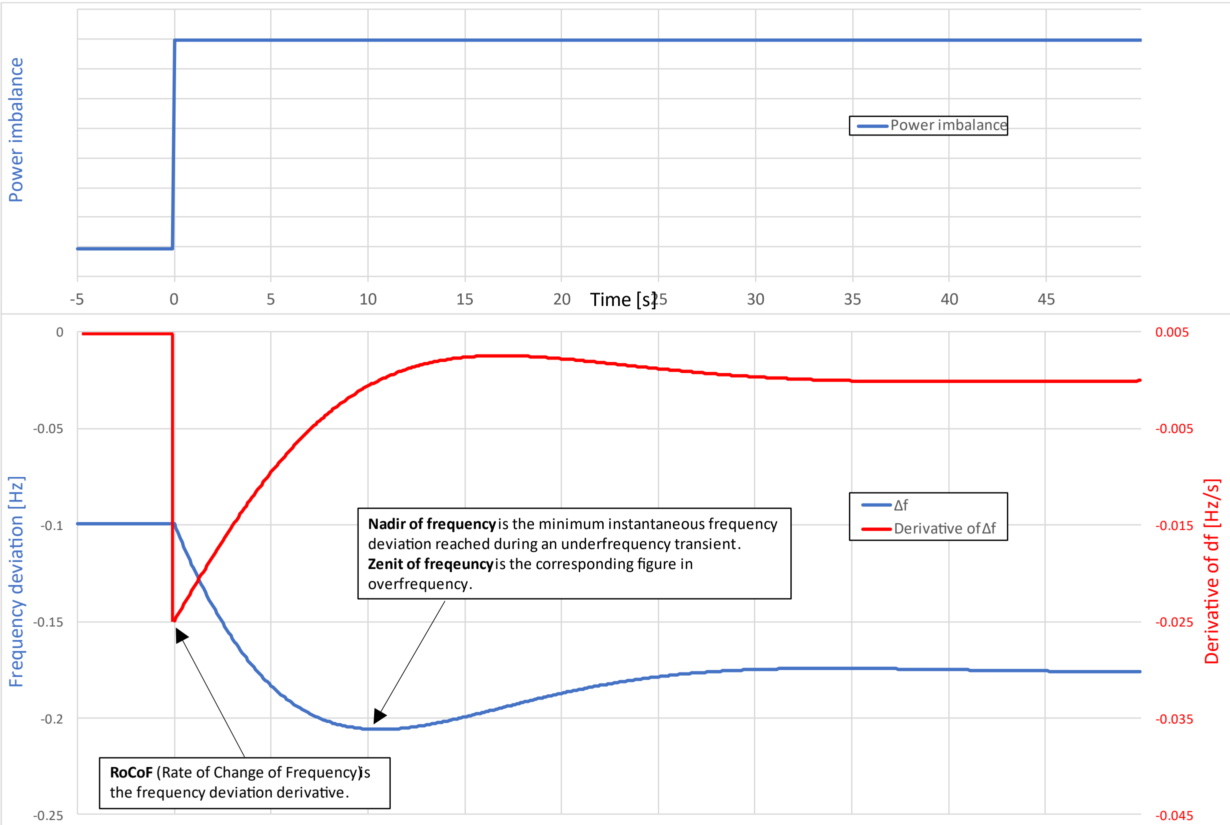

Figure 7: Example of frequency transient characteristics and main performance indicators: zenit, nadir and RoCoF

Given the wide number of transient to be calculated for the dimensioning exercise, it is unfeasible to perform an actual dynamic simulation in each single minute. There is therefore the need to adopt an algebraic calculation of zenit/nadir and ROCOF starting from the aggregated single-busbar model depicted in Figure 8, based on considerations from [2].

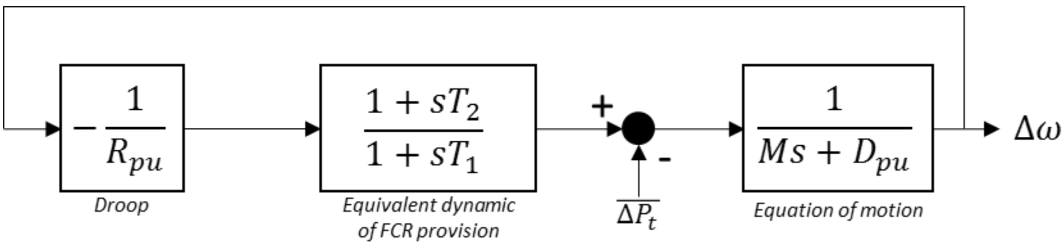

Figure 8: Simplified single-busbar dynamic model of the CE power system

Where:

- **Equation of motion**: represents the response of the power systems in terms of inertia and self regulation of load;
- **Droop**: represents the static response of the FCR (see Figure 4);
- **Equivalent dynamic of FCR provision**: represents the average combined effects of the dynamic responses provided by all FCR providers.

The parameters presented in Figure 8 are thus:

$R_{pu} = \frac{1}{En.Reg.} \cdot \frac{P_n}{f_n}\ [pu_P/pu_{\Delta f}]$	Droop in pu ($En.\ Reg.$ is associated with a certain MW/Hz curve and it's expressed in [MW/Hz])
$T_1\ [s]$	Pole time constant of average FCR dynamics
$T_2\ [s]$	Zero time constant of average FCR dynamics
$D_{pu} = \frac{D}{f_n} [pu_P/pu_{\Delta f}]$	Self-regulation of load (D is expressed in [pu/Hz])
$M = 2 \cdot H\ [s]$	System equivalent angular momentum (2*Inertia)
$P_n\ [MW]$	Load at SA level
f_n	Nominal frequency (50 Hz)

The output of the diagram ($\Delta\omega$) is the frequency deviation in pu.

Considering the actual and complex dynamics of the SA, with this model significant approximations are introduced, since each provider (and each technology) has its own peculiarities when it comes to the FCR deployment dynamic. Such variety of responses is simplified with a single 2^{nd} order dynamic model in order to derive the algebraic formulas for Zenit/Nadir and ROCOF. The ROCOF is evaluated as the initial ROCOF.

Such formulas are derived assuming that a stepwise disturbance is applied on the model presented in Figure 8.

In this way an algebraic relationship between the disturbance and the system parameters can be used within the iterative probabilistic model.

The calculation of dynamic performances of frequency deviations are based on the same 1-minute granularity adopted for the steady state calculations. It means that all the variables (e.g., power imbalance and steady-state frequency deviation) continue to change minute-by-minute.
Both the transient frequency peak (zenit/nadir) and the ROCOF are therefore calculated on a 1-minute basis.

The input of such calculation is the difference of power imbalance between two following minutes.

2.8 Assessment of the acceptability criteria on the resulting simulated frequency deviation

A FCR dimensioning shall be considered acceptable if ensures that the FCR is insufficient not more often than once every 20 years.

The first step is to assess whether a specific minute is considered an acceptable minute. A minute is considered an acceptable minute if it fulfills all the following three criteria:

- The absolute value of the simulated steady state frequency deviation does not exceed the steady state maximum frequency deviation;

- The absolute value of the maximum/minimum instantaneous frequency deviation during transients doesn't exceed the thresholds defined by the TSOs;
- The absolute value of the ROCOF does not exceed the Maximum Initial ROCOF as defined by the TSOs?

A minute is considered a not acceptable minute if at least one criterion is not fulfilled.

To interpret the «once in 20 years» criterion, the concept of "Critical Condition" is then introduced: a Critical Condition is a series of not acceptable minutes spaced each other not more than a parametrical number of minutes (e.g., 15 minutes).
A single Critical Condition could then be made by several following minutes with one or more criteria not fulfilled.

The choice of such approach is related to the fact that the combination of disturbances causing a condition where one or more criterion (SSΔf / zenit/nadir / ROCOF) are not fulfilled could persists for several minutes.

The «once in 20 years» criterion is applied on the number of Critical Conditions rather than on single minutes. The FCR dimensioning is thus aimed at ensuring that the number of detected Critical Conditions is less or equal to 1/20 of the number of simulated years.

E.g., if 200 years are simulated by the model, no more than 10 (200/20) Critical Conditions shall occur.