European Network of
Transmission System Operators
for Electricity

Frequency Measurement Requirements and Usage

- Final Version 7 -

RG-CE System Protection & Dynamics Sub Group

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1. Contents

2. Scope of this document

Frequency measurements are the key ones in power systems. Therefore, a common understanding of the way in which these measurements are performed and processed within an interconnected system is necessary. This document focusses on main and common aspects regardless of whether a frequency measurement is performed for a power generating unit or a load shedding relay. At the same time, it does not address the details of signal processing. The main focus is on the entire interconnected system behaviour mainly emphasizing electromechanical transients. Functional criteria are addressed which are needed for robust frequency measurements required for power system control and power system protection.

3. Practical example of a frequency measurement

Two recent recordings performed by data acquisition from PMUs shall illustrate in a practical way the range of interest for the required frequency measurements.

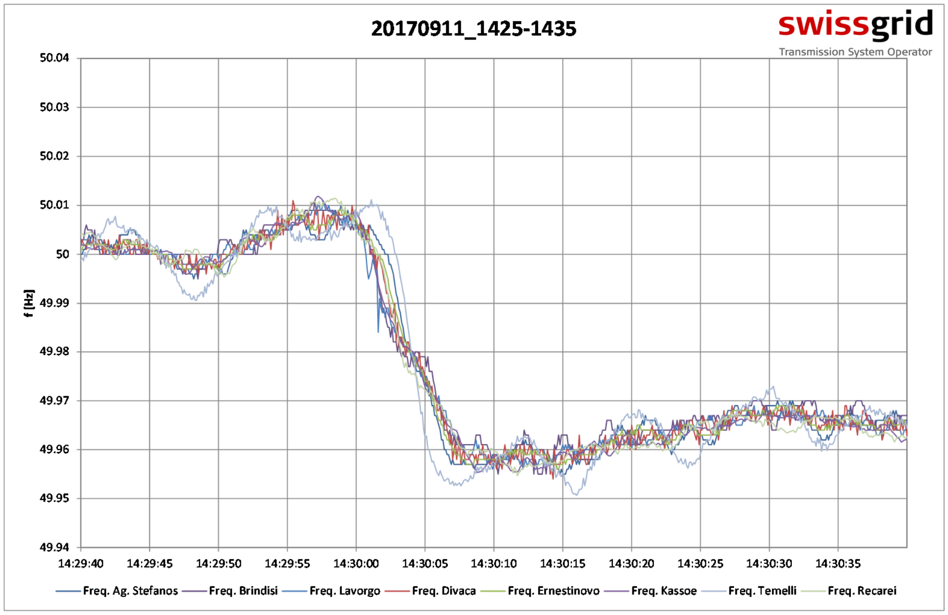

Fig. 1: Forced Outage of 1000 MW Generation in Switzerland – PMUs recording (100 ms report rate)

It can be clearly seen that the “centre of inertia” for this event is close to Ernestinovo (HR) – green line, and that the highest delay in frequency response of about 4 seconds is at Temeli (TR) – light blue line, as well as that the first visible response is from Lavorgo (CH) – dark blue line. The frequency drop is 40 mHz and a RoCoF in the range of 10 - 15 mHz/s can be computed applying the criteria of main frequency evaluation with respect to electromechanically behaviour.

In **Fig. 2** a frequency deviation in the opposite direction – loss of load/HVDC link – during 1000 MW of export to another synchronous area (Great Britain) is depicted.

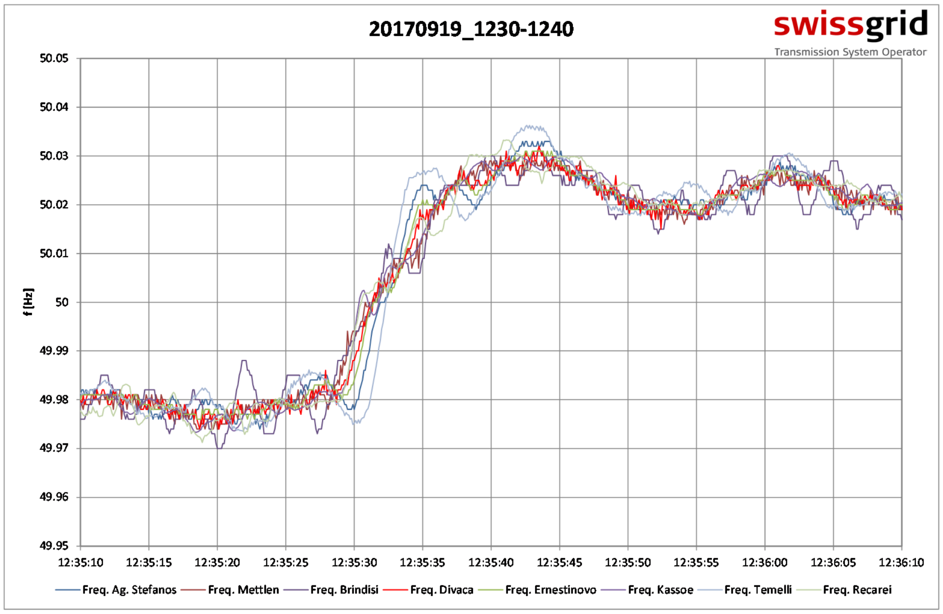

Fig.2: Forced Outage of 1000 MW export FR-GB Link – PMUs recording (100 ms report rate)

Similar to the previous recorded event, the frequencies are aligned around the highest rate of change of frequency (RoCoF) from Recarei (PT) as the closest point/available PMU measurement to the outage, and Temeli as the furthermost point, whereas Divaca (SI) and Ernestinovo (HR) are the closest points to the centre of inertia again. Here, the steady-state frequency increase is 43 mHz with a RoCoF of 10 – 17 mHz/s.

The examples shown aim at pragmatically illustrating physical phenomena: the frequency is, in phasor domain, a function (derivate) of the voltage phasor angle on the busbar where is measured. Figure 1 and 2 demonstrate that applying a report rate of 100 ms to the recording permits revealing interarea oscillations. This kind of frequency measurement is adequate for studying electromechanical oscillations and small signal stability; as we can see, it is also possible to note that a perturbation has a propagation time over the system. In fact, Figure 1 demonstrates that the propagation (frequency transient) time from Switzerland (source of disturbance) to Turkey is around 4 seconds. This kind of approach was also adopted to model the European power system at nodal level; SPD SG produced an “initial dynamic model”[1] with the aim at providing an instrument capable of reproducing electromechanical transients.

Fig. 3 illustrates the typical time constant ranges versus phenomena.

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[1] The initial dynamic model is continuously under update and maintenance by SPD SG experts; more information is available on ENTSOE site [4].

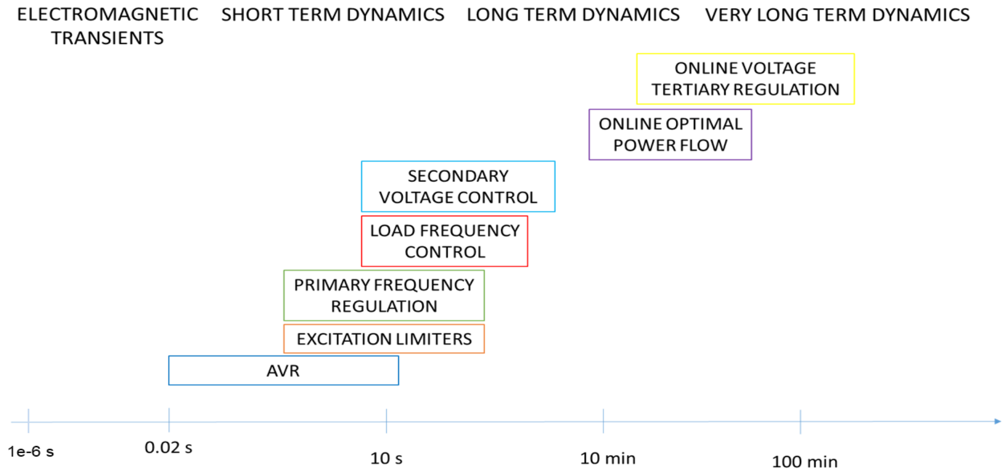

Fig.3: Dynamics behaviour versus time constants

When referring to system behaviour involving primary frequency control, secondary power frequency control, load shedding plans, and RoCoF prescriptions, the main assumption is that the frequency is the same all over the grid. Consequently, the mathematical model is one equivalent busbar representing the whole system, to which the equivalent elements such as generator, load, etc. are connected.

In this case, the frequency is called "mean equivalent frequency", as is showed in the yellow dotted line in **Fig. 4**. The RoCoF calculation in simulations is referred to this frequency. The next chapters show how to filter the local frequency in a way to obtain the mean system frequency.

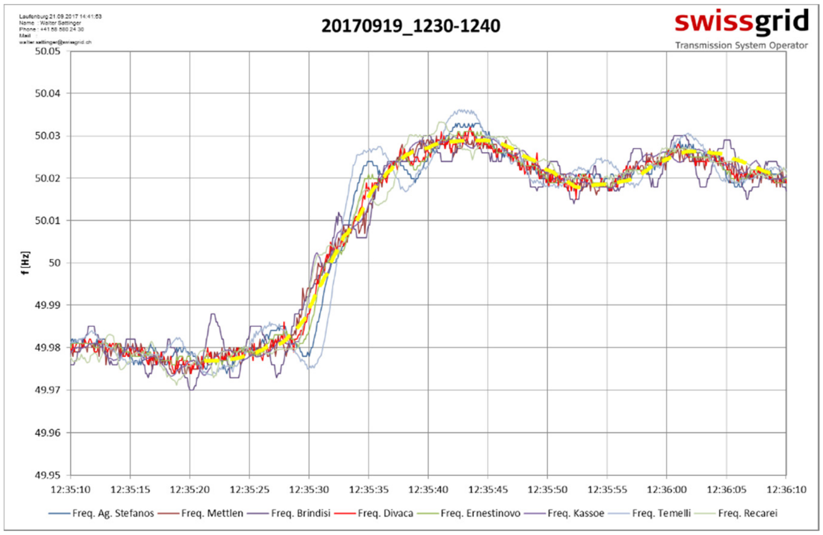

Fig.4: Mean frequency of the system

4. Frequency measurement functional criteria and key parameters

4.1 Physical concept of frequency

Let us consider a voltage measurement on an electrical node. In three-phase systems it is possible to associate an equivalent voltage phasor that can be written as follows:

$$V(t) = V_O(t).\sin(\omega.t + \theta)$$

Alternatively if can be written $V(t) = V_0(t).\sin(\phi(t))$

Where $\phi(t) = \int_0^t \omega(x)dx$

Where:

- ω is the pulsation in rad/s
- t is time expressed in seconds
- θ is the angle displacement versus the reference phasor
- V_0 is the voltage amplitude in kV
- ϕ is the absolute angle of the voltage phasor

The frequency of the sinusoidal voltage is $f = \frac{\omega}{2 \cdot \pi}$

This definition is simple and can easily be applied to steady sinusoidal waveforms. Currently, there are several algorithms and methods available to estimate the frequency, mainly based on:

- Phase Locked Loop
- Fast Fourier transformation
- Zero crossing of sinusoidal measurements, mainly busbar voltage used
- Synchrophasor estimation and derivation of angle.

By definition, constant frequency is used for steady-state signals. However, in power systems the frequency of the voltage is continuously changing. Therefore, special algorithms need to be applied. Some digital measurement device claims to have a very high frequency measurement reporting rate, but the shorter the time for frequency calculation, the noisier the measurement.

The influence of the frequency measurement due to harmonics (subharmonics, phase angle jumps, faults in the grid) becomes particularly problematic in case of frequency derivative calculation. For high reporting rate, a small deviation between two time steps can lead to a very high value of derivative of frequency.

In conventional power systems, the frequency is imposed by synchronous generators. Therefore, the physical inertia of these rotating masses limits the frequency variation and the frequency can be filtered or calculated over a longer period to avoid noise and smooth its behaviour.

Taking into account these concepts, the basic frequency calculation algorithm, considering a sampling rate[2] Δt and discrete samples ϕ_i, f_i can be expressed as:

$$f(t) = \frac{d\phi(t)}{2 \cdot \pi \cdot dt} \Rightarrow \frac{\phi_i - \phi_{i-1}}{2 \cdot \pi \cdot \Delta t}$$

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[2] Unlike the measurement window in protection devices, here 20 samples means one sampling for each ms

$$ROCOF = \frac{\partial f(t)}{\partial t} = \frac{\partial^2 \phi(t)}{\partial t^2} \Rightarrow \frac{f_i - f_{i-1}}{\Delta t}$$

From this it follows that RoCoF and frequency need to be referred to a specific dynamic behaviour and reporting rate to create a link with studies or real recordings.

With regards to real time frequency estimation techniques, the literature offers a large suite of possible algorithms; for examples see [1] [2] [3].

It is worth of noting, as an example from [1], how different algorithms influence the frequency estimation and consequently the RoCoF calculation.

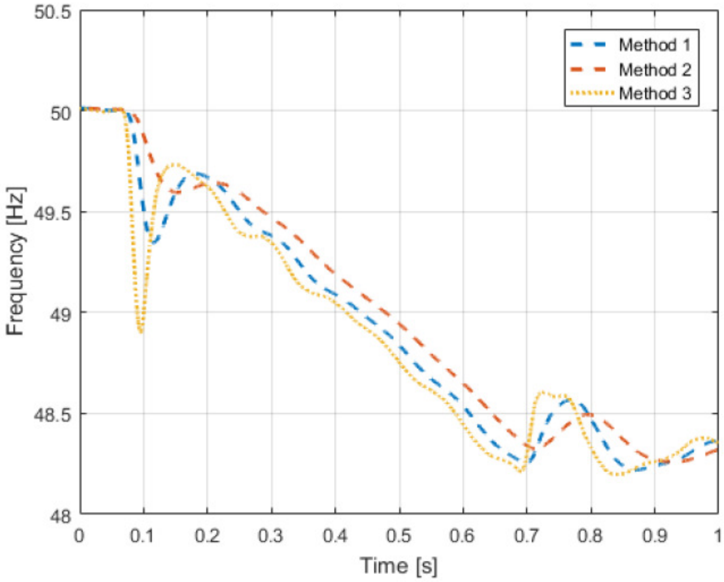

Fig. 5: Figure extracted from [3] showing the performance of three different estimation algorithms processing a simulation output

The key factor is to "filter" the measured frequency from the dynamic behaviour near to electromechanical transients by either classical filtering resulting in a signal delay or stabilisation measures like elimination of single samples or freezing the measurement or other additional average calculations. No particular recommendation on low pass filtering approach can be given due to the fact that a wide range of different filter algorithms are actually available, i.e.:

- Bessel
- Butterworth
- Chebyshev
- Elliptic.

The main constraints for filter parameters are:

- High dependency of the frequency characteristic on the filter design in order to be insensitive to high frequency noise and spikes as much as possible
- Minimization of the delay introduced by the filter.

For system studies, it is suggested to use 10 Hz reporting rate for the frequency calculation rate, adequate to perform frequency calculations in line with a typical reporting rate managed by PMUs. The RoCoF can be obtained applying the formula previously reported taking into account that the RoCoF is very sensitive to noise; in such situations the RoCoF calculation is additionally smoothed with a 500-1000 ms measurement sliding window.

All this means that the calculation procedure must include a kind of filtering in order to reject or smooth the samples leading to a wrong RoCoF calculation.

Many phenomena that occur in the grid can disturb the local frequency measurement. Amongst others, short circuit, topology change, and energization of transformers can be mentioned. These phenomena can lead to a very fast variation of local frequency. To minimize the impact of such event on the grid through misbehaviour of device, the frequency measurement should be low-pass filtered to remove noise from the calculation.

The low-pass filter can be adjusted depending on the use of frequency measurement: synthetic inertia will need a fast measurement while for frequency sensitive mode FSM a much slower measurement is required.

These “wrongly” measured frequency values are mainly generated by phase jumps induced by discontinuities near the electrical node where the frequency is calculated. This, for example, can be short circuits or topology changes (i.e. energization of power transformers, busbar change, etc.) that involve circuit breaker or disconnector manoeuvres. These phenomena usually have only a local impact on the frequency. The influence of this can be minimized by introducing a proper filtering on the acquired measurement in such a way that the correct frequency behaviour (for electromechanical use or “mean frequency” application) is reproduced. However, for applications that require fast reaction, this cannot be done as it is impossible to discriminate in a fast and robust way a local frequency “jump” from a global fast frequency deviation. Fortunately, as mentioned before, these phenomena only produce a local frequency perturbation and the adverse effect will, therefore, be negligible compared to the overall system behaviour, but it can cause local under frequency load shedding operation or disconnections of e.g. photovoltaic installations if the local frequency reaches the set value (e.g. 49 or 50.2 Hz).

4.2 Technical requirements

As the frequency measurement is based on the evaluation of the power system voltage, the related frequency computation needs at least the evaluation of a few cycles, typically 90 ms - 120 ms. In conclusion, there is always a trade-off between **fast** enough and sufficiently **precise** frequency values. In other words, the frequency measurements required for system or equipment protection cannot be as accurate as the frequency processed in the range of a few 100 milliseconds for power generation or power system control.

For an accurate **RoCoF** calculation experience has shown that a sliding window over approximatively five consecutive measurements gives robust results which in the case of 100 ms time resolution results in 0.5 seconds time required before a reliable RoCoF value can be available.

The typical selectable range of accuracy is 10 mHz with a measurement window of 100 ms; based on pragmatic experience it is also possible to admit a maximum total harmonic distortion of 3 % (THD). The phase imbalance also plays an important role. The maximum acceptable value is 3 %. It is suggested to execute the frequency measurement as far as possible close to busbars with a high short circuit power in order to avoid additional filtering.

4.3 Example of noise effect

Fig. 6 reports a real recording of a frequency measured near an industrial area with a reporting rate of 20 ms. As can be noted the measurement has a significant content of high frequency noise.

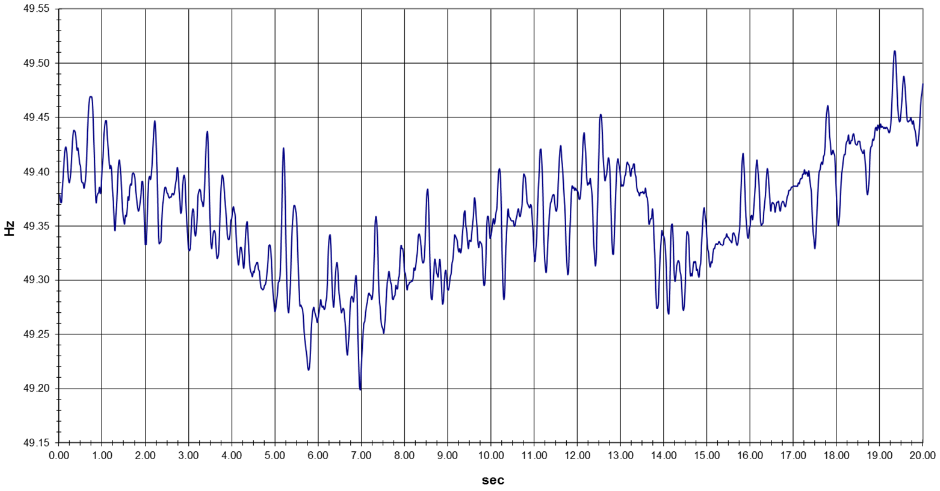

Fig. 6: Real frequency recording on ENTSOE grid (medium voltage level in noisy industrial environment) – 20 ms reporting rate

Applying the calculation of RoCoF we can note that obtained values (in orange) are very noisy; an average shifting over 500 ms gives a more realistic result. It is clear that this simple filtering is adopted only with the aim to provide an example. As discussed previously, more sophisticated filters can be applied to eliminate high frequency components.

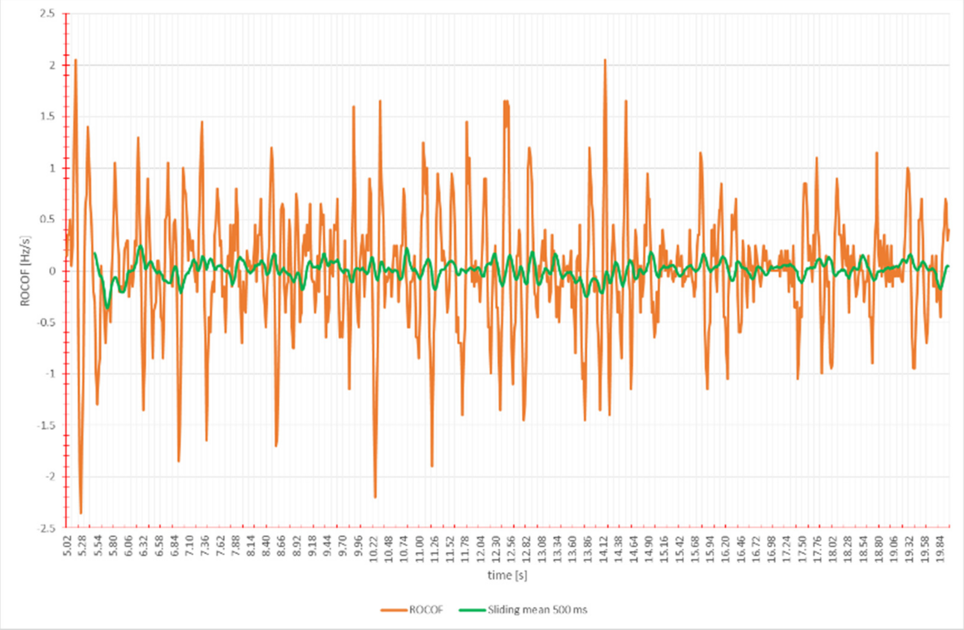

Fig. 7: RoCoF filtering (green colour) and un-filtered (brown colour)

4.4 Synthesis of technical requirements

Frequency measurements can be used in different applications. **Table 1** summarizes how different applications in power systems are based on different ranges with respect to:

- Measuring time window that influences the performance of the application but at same time it represents the minimum time needed to avoid wrong calculations
- Accuracy.

Table 1: Frequency Measurement Requirements

Application	Meas. Window / ms	Accuracy	Comments
Protection	90-120[3]	30 mHz	generation unit, underfrequency load shedding
Local control	100-200	10 mHz	decentralised generation control
Centralised control	500	1 mHz	centralised generation control (AGC)
LFSM	100	50 mHz	system control, system protection
RoCoF	180-240	50 mHz/s	additional protection criteria for generation or load
RoCoF	500-1000	1 mHz/s	evaluations on synchronous area level

There are cases of higher needs for power plant protection, which are not mentioned here.
However, these requirements cover compliance tests, monitoring needs and offline analysis of events as well as generation unit responses e.g. RoCoF withstand capability. If an artificial frequency signal is used for testing, the related measurement time will have to be considered correspondingly. For compliance simulations it might even be better to generate the relevant variables as given boundary conditions.

Insensitivity and accuracy are strongly related in a way that the sum of both shall not exceed the values obtained only as accuracy.

Measurements based on mechanical elements are allowed as long as they provide a sufficiently fast measuring time and the required high accuracy.

Measurements based on voltages with a high level on harmonics or phase jumps need a quite long measurement window and deliver less precise results.

5. Conclusions

The document clarifies the concept of frequency measurement and its use for dynamic evaluations in the domain of interconnected system behaviour. It distinguishes the “local” or interarea frequency oscillation from the mean frequency of the system. These different definitions can help to address the concept of system RoCoF correctly. In order to measure and calculate a correct and robust frequency, some functional guidelines are recommended, by giving some real recording examples of critical situations in terms of

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[3] Protection equipment operate time

potentially noise affected calculations. In the last part, a table resumes the most significant parameters to be considered in the frequency measurement design.

6. References

[1] A. Carcelen-Flores, J.A. Fuentes, A. Molina-Garcia, E. Gomez-Lazaro, and A. Vigueras-Rodriguez, “Comparison of Instantaneous Frequency Estimation Algorithms under Power System Disturbances”, Proc. 2012 IEEE PES GM, July 2012.

[2] Boualem Boashash, “Estimating and interpreting the instantaneous frequency of a signal-Part 1, Proc. IEEE vol. 80(4), pp 540-568,1992

[3] Sonke Engelken, Christian Strafiel, Eckard Quitman, “Frequency Measurement for Inverter-based Frequency Control”

[4] ENTSO-E, Initial model of Continental Europe, 2015, https://www.entsoe.eu/publications/system-operations-reports/continental-europe/Initial-Dynamic-Model/Pages/default.aspx

7. Abbreviation List

AGC	Automatic Generation Control
FSM	Frequency Sensitive Mode
LFSM	Limited Frequency Sensitive Mode
PMU	Phase Measurement Unit
RoCoF	Rate of Change of Frequency
SPD	System Protection and Dynamics SG
THD	Total Harmonic Distortion