



Preliminary study of large-frequency oscillations in south-west Spain

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Background

Between 18:00 and 20:00 CET (17:00-19:00 UTC) on 11 December 2025, frequency and voltage oscillations were larger than usual in Seville (southwest, Spain).

The measurement was taken with a *UNDAM*[®] *uMETER 500* in LV. The reporting rate was set at 100 samples per second (every 10 milliseconds) with synchronous recording at each 10-millisecond UTC tick. Frequency, ROCOF and voltage were measured by taking simultaneous windows of 1, 5, 10, 25 and 50 cycles, thus capturing even the most sensitive and slower oscillations.

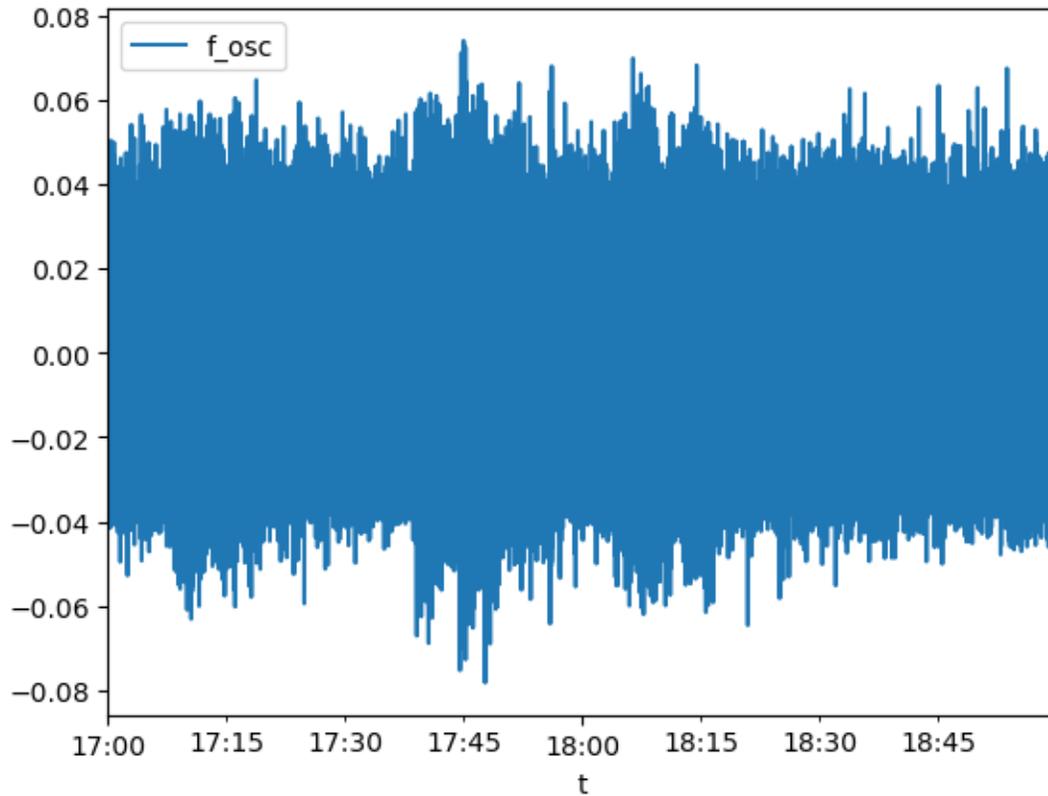


To assess whether these oscillations were widespread throughout Spain, measurements were compared with those taken by another device in Barcelona, in northeast Spain.

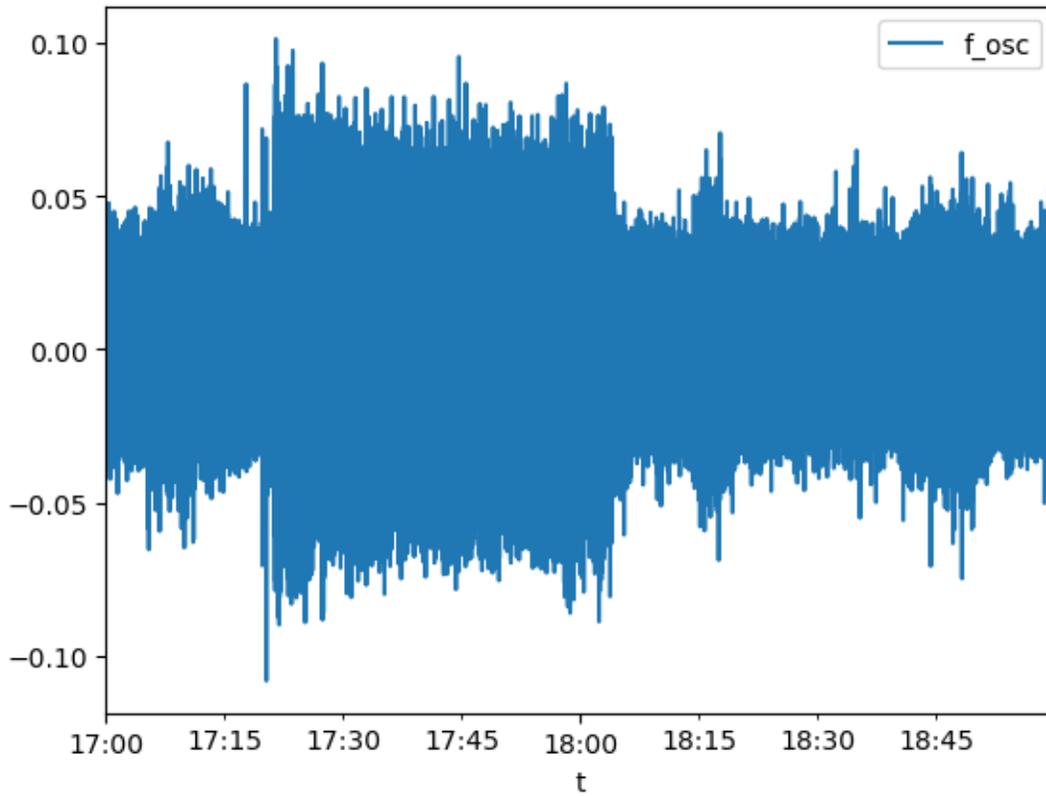
NOTE^{new!}: between 20:00 and 21:00 CET (19:00–20:00 UTC) on 29 December 2025, new and stronger oscillations were detected once more. This will be explained in a separate chapter.

Measurements

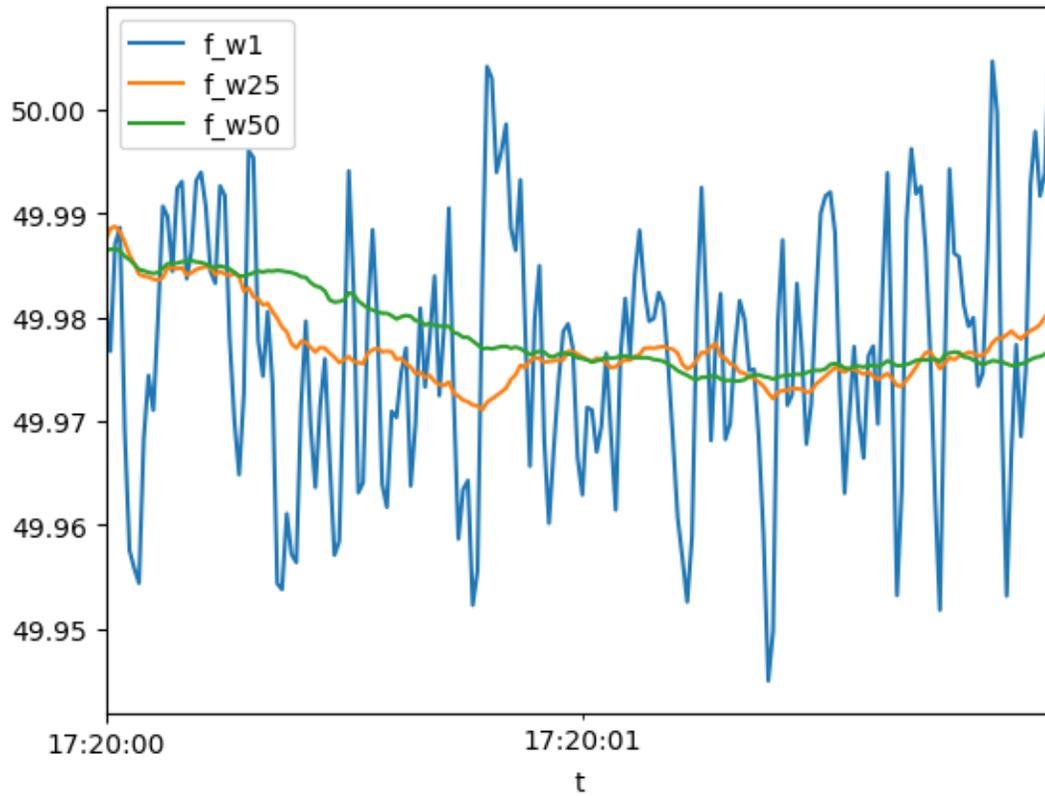
In Barcelona, the oscillation frequency was around ± 60 mHz, taken as the difference between the 1-cycle and 50-cycle measurements. It was sometimes slightly higher.



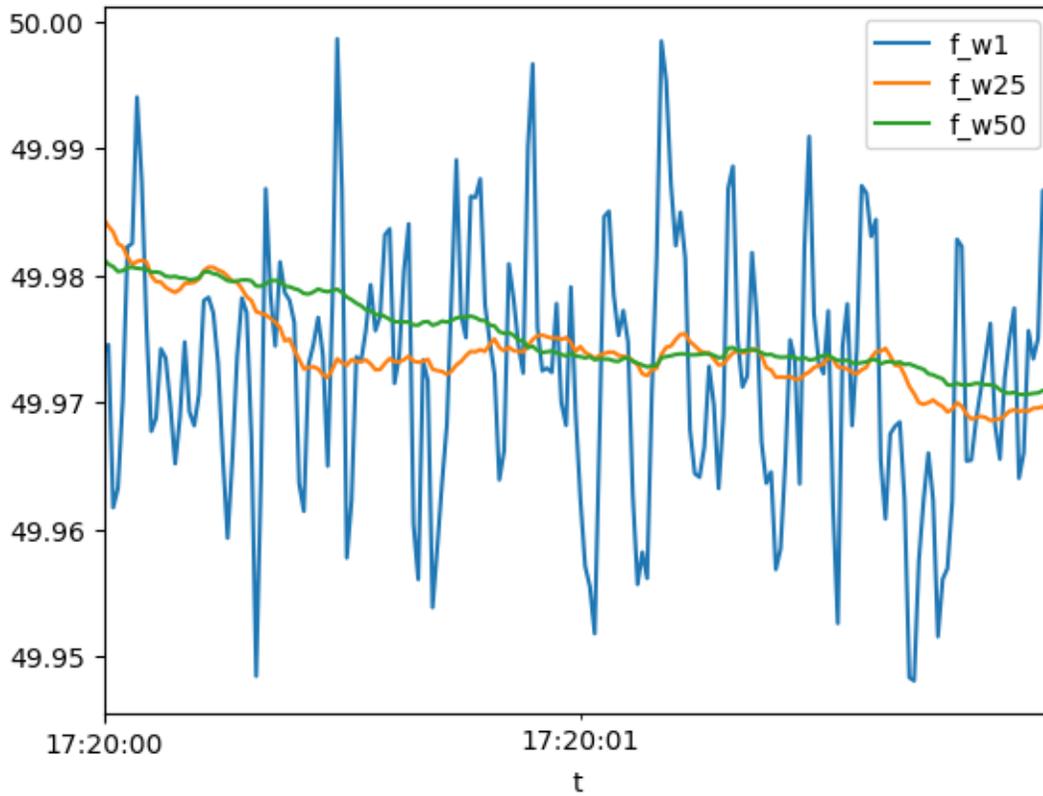
Seville experienced a larger frequency oscillation, with a significant increase that lasted around 40 minutes.



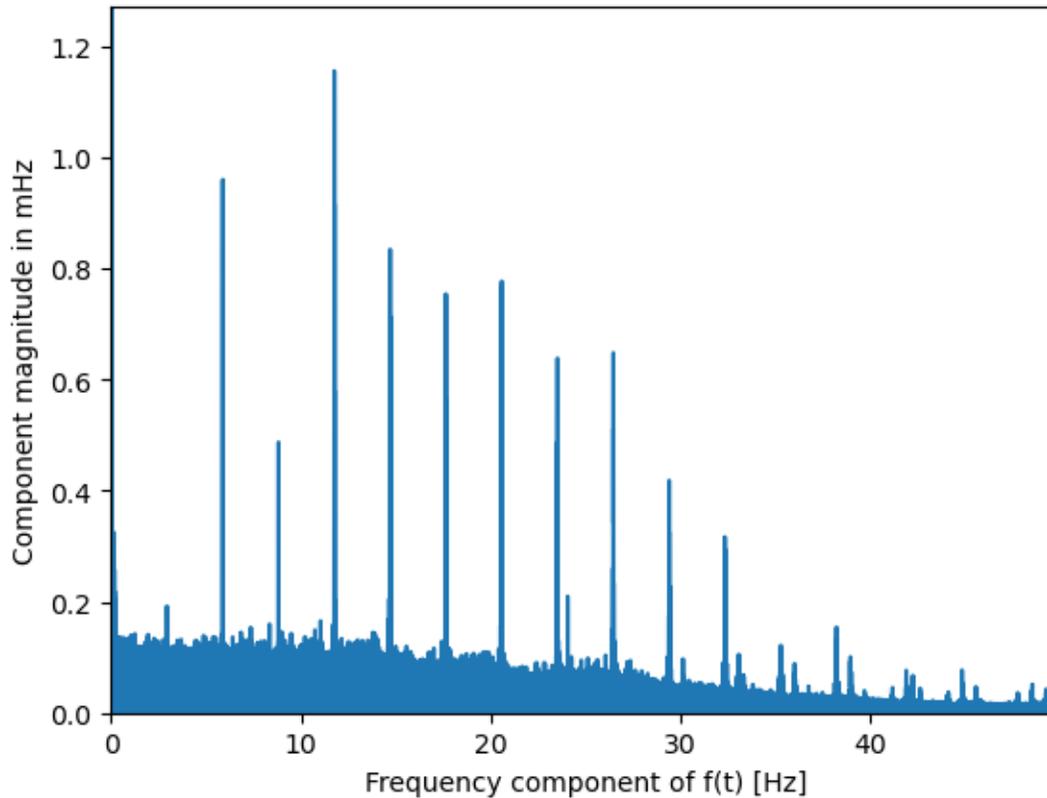
Zooming in by 2 seconds reveals a rapidly decreasing 50-cycle frequency and a highly oscillating 1-cycle frequency in Barcelona.



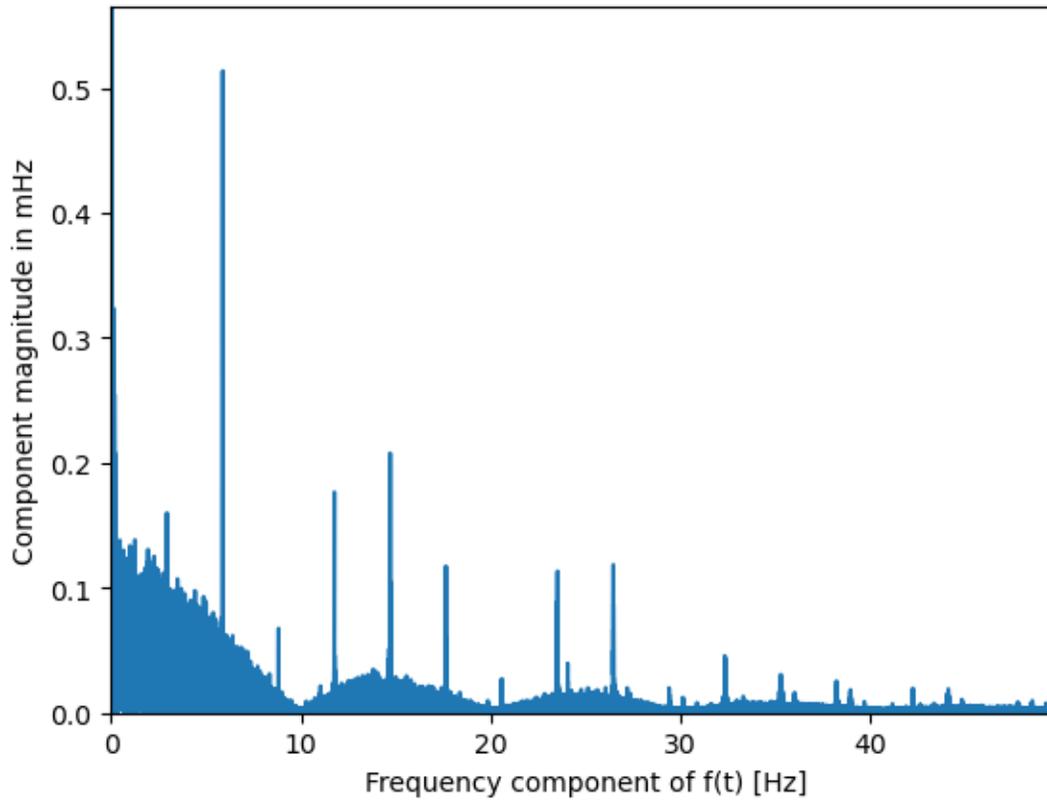
Seville exhibited a similar pattern, although the peaks and repetition were more clearly defined.



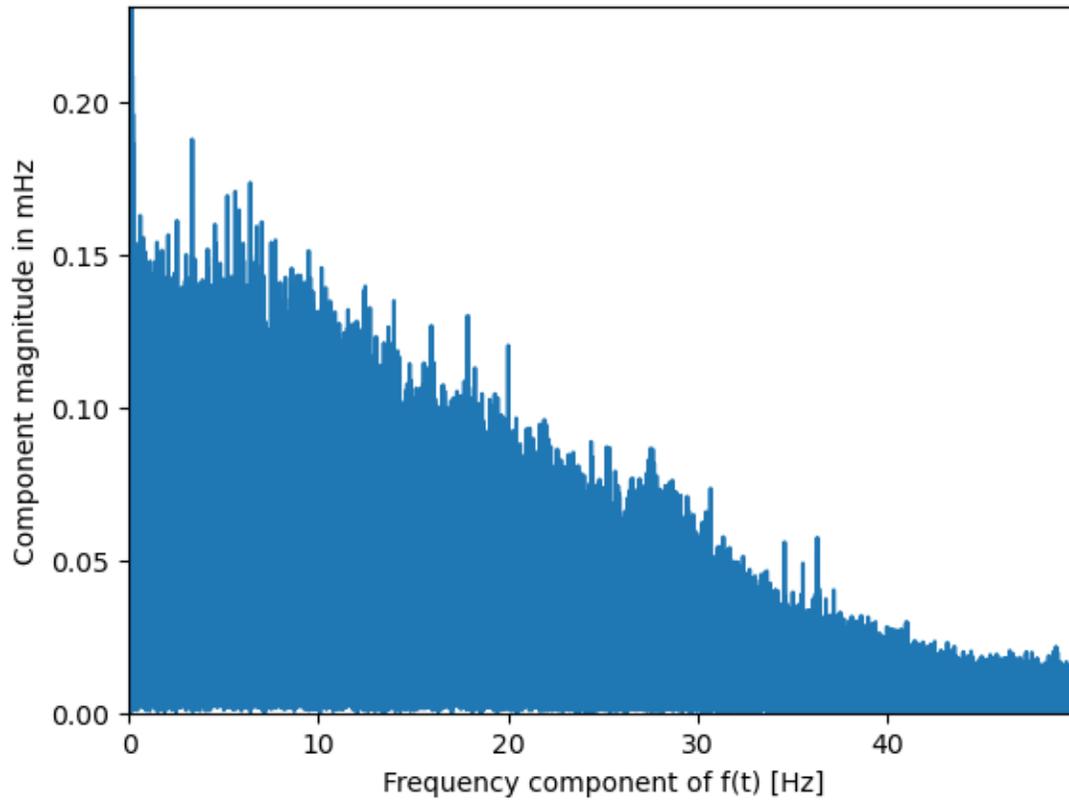
What makes this really strange is the very clear FFT analysis of the frequencies in Seville. The frequencies have components every 2.94 Hz. The largest component is at 11.76 Hz.



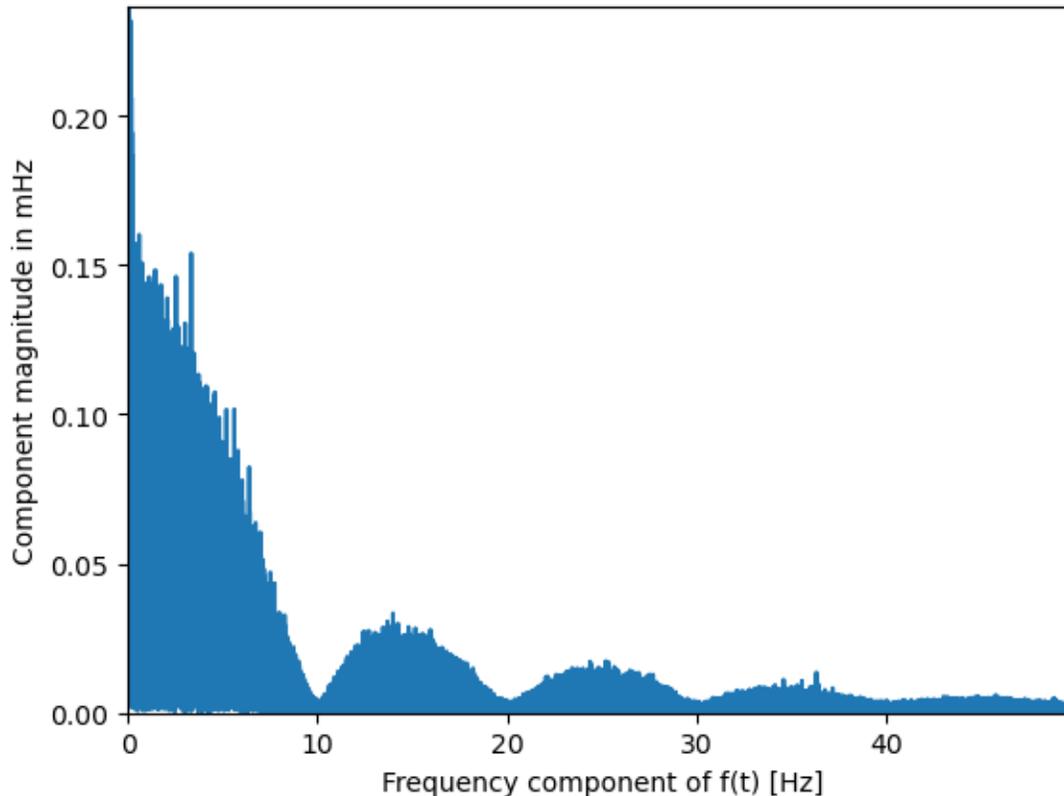
If the calculation window is increased to five cycles in order to compare the chart to a typical M-type PMU, artefacts appear between the 10 Hz multiples, as expected. Furthermore, the absolute and relative magnitudes of the harmonics change; the highest is 5.88 Hz. This is logical because the 5-cycle averaging window corresponds to 10 Hz, which is above the previous 11.76 Hz. This demonstrates that using 5 cycles will mask and flatten any modulation above 10 Hz.



On the contrary, Barcelona does not show any dominant frequency, slowly decreasing from the DC component (49.99 Hz) almost linearly.



If five cycles are taken, then the expected artefacts show up, but not the harmonic components as seen in Seville.



Analysis of the detected frequencies^{new!}

The FFT analysis of the recorded window revealed several frequency bins that were difficult to explain. However, it will be demonstrated that this is due to a combination of aliasing and sudden ROCOF bumps, which were identified using the *UNDAM*[®] *uMETER 500*.

Taking into account that frequency can be calculated over just one cycle, perfect modulation of the fundamental would appear as two bins on either side of it. These would then be aliased back as mirror frequencies around the Nyquist frequency (25 Hz), appearing as frequencies between 25 and 50 Hz and 50 and 75 Hz.

If perfect modulation were considered, just two bins would be present on either side and one below the Nyquist frequency. For example, a modulation of 50 ± 2.94 Hz would result in a DC component at 50 Hz and one bin at 2.94 Hz. A modulation of 50 ± 5.88 Hz would show a bin at 5.88 Hz. However, this is not what is seen in the FFT, where a full spectrum of bins is present.

However, if we assume that the modulation is imperfect and there is a set of bins on either side of 50 Hz, this would also show up as many bins below the Nyquist frequency.

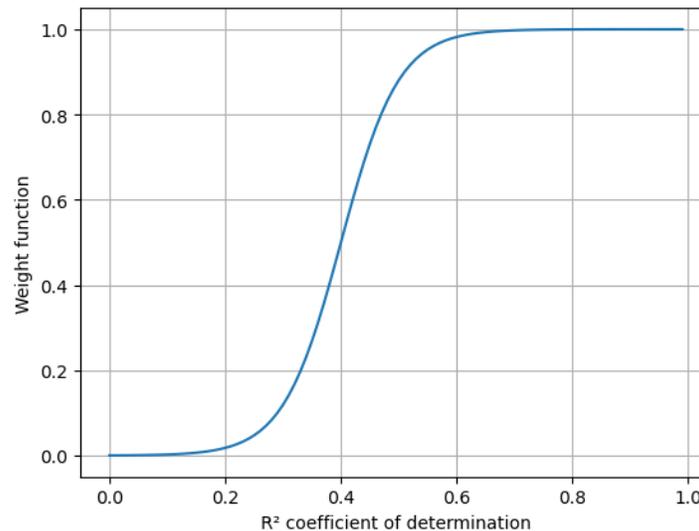
If the set of bins were at $50 \pm p \times 2.94$ Hz, the expected frequencies would be 2.94, 5.88, 8.82, 11.76, 14.70, 17.64, 20.58 and 23.52 Hz. If the set were at $50 \pm p \times 5.88$ Hz, the expected bins would be at 2.96, 5.88, 8.84, 11.76, 14.72, 17.64, 20.60 and 23.52 Hz. Therefore, the results would be almost identical, with the slight differences being within the error range. Since 5.88 Hz is the largest component, the base modulation should be at this frequency, rather than at 2.94 Hz.

However, it will be demonstrated that this is not only an aliasing phenomenon of continuous mains frequency modulation, but that it jumps in steps rather than continuously. An analogy would be a heart, where the fundamental frequency is seen as a sequence of beats.

Indeed, the *UNDAM*[®] *uMETER 500* is able to measure the ROCOF within just one cycle (not by difference of two adjacent cycles, but by measuring the internal average slope within the cycle). Since this measurement comes from the best linear approximation, it provides the uncertainty and the coefficient of determination (R^2) of the calculation. This makes it straightforward to determine whether the estimated ROCOF is representative. The coefficient of determination yields a value between 0 and 1, which can be used to assess the ROCOF value.

This is achieved by applying an arbitrary weight function. In this case, the well-known sigmoid function is used, which resembles a soft step to make the function less abrupt.

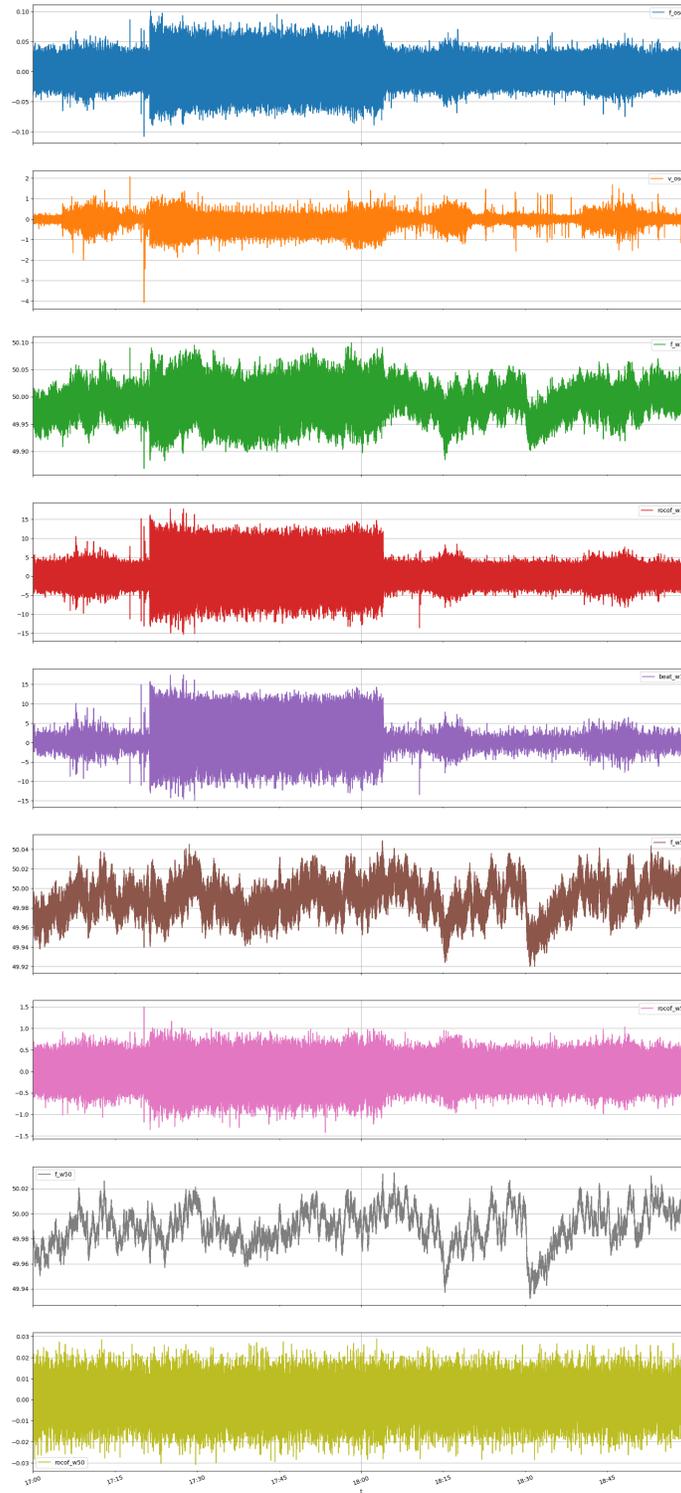
$$w(R^2) = \frac{1}{1 + e^{-20(R^2 - 0.4)}}$$

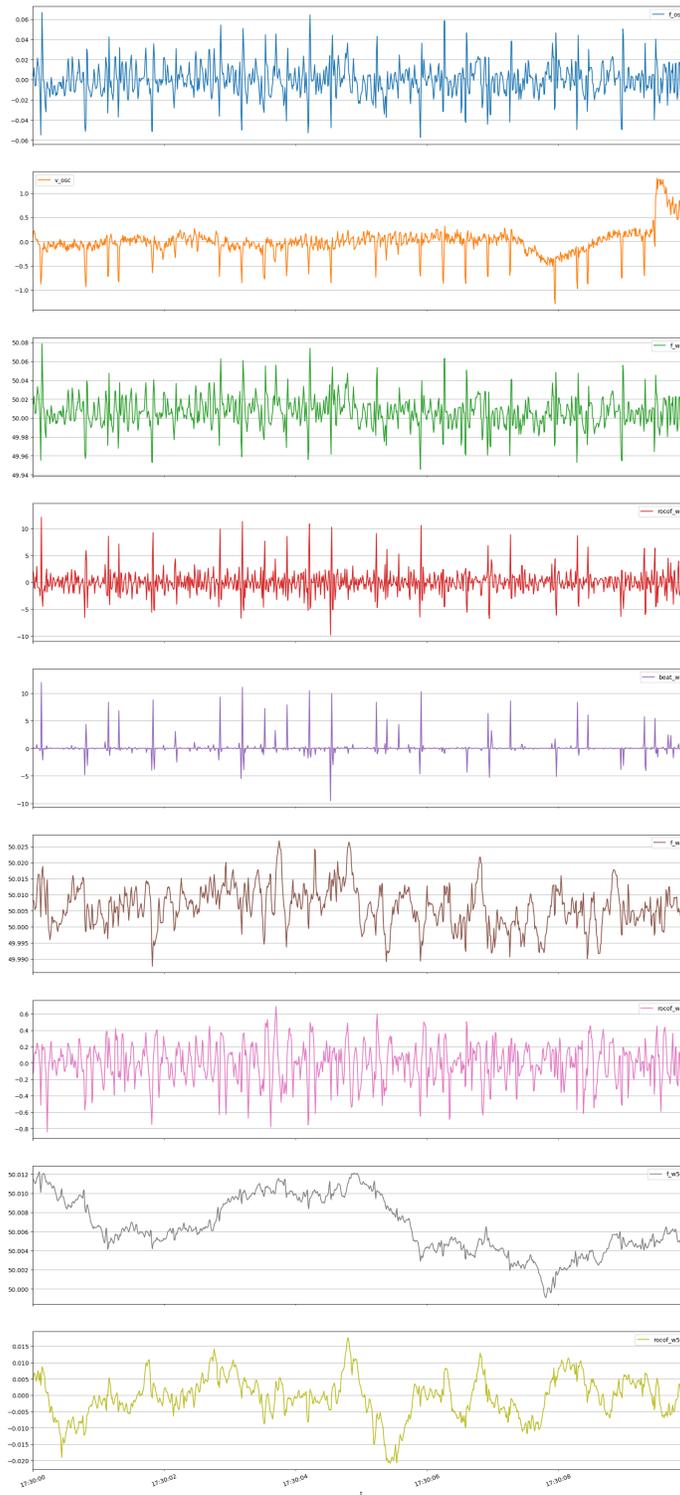


This function is multiplied by the ROCOF over one cycle to provide a more accurate evaluation of the ROCOF and to highlight the frequency slope beats. By *beats*, we mean sudden frequency changes within one cycle that remain fairly constant, thus achieving a sufficiently large R^2 value (e.g. above 0.6).

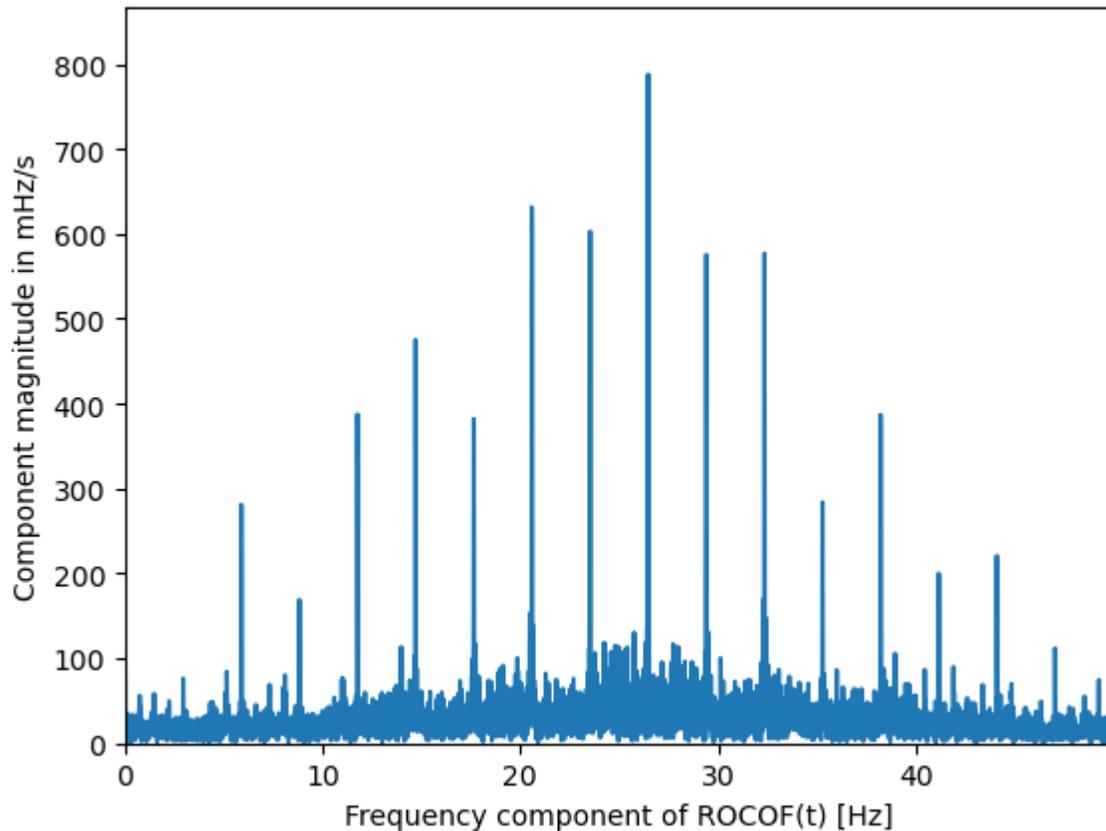


Next is a series of charts showing the short-term oscillation frequency and voltage, the 1-cycle frequency and ROCOF (unweighted), the weighted 1-cycle ROCOF, and the frequency and ROCOF over 5 and 50 cycles.





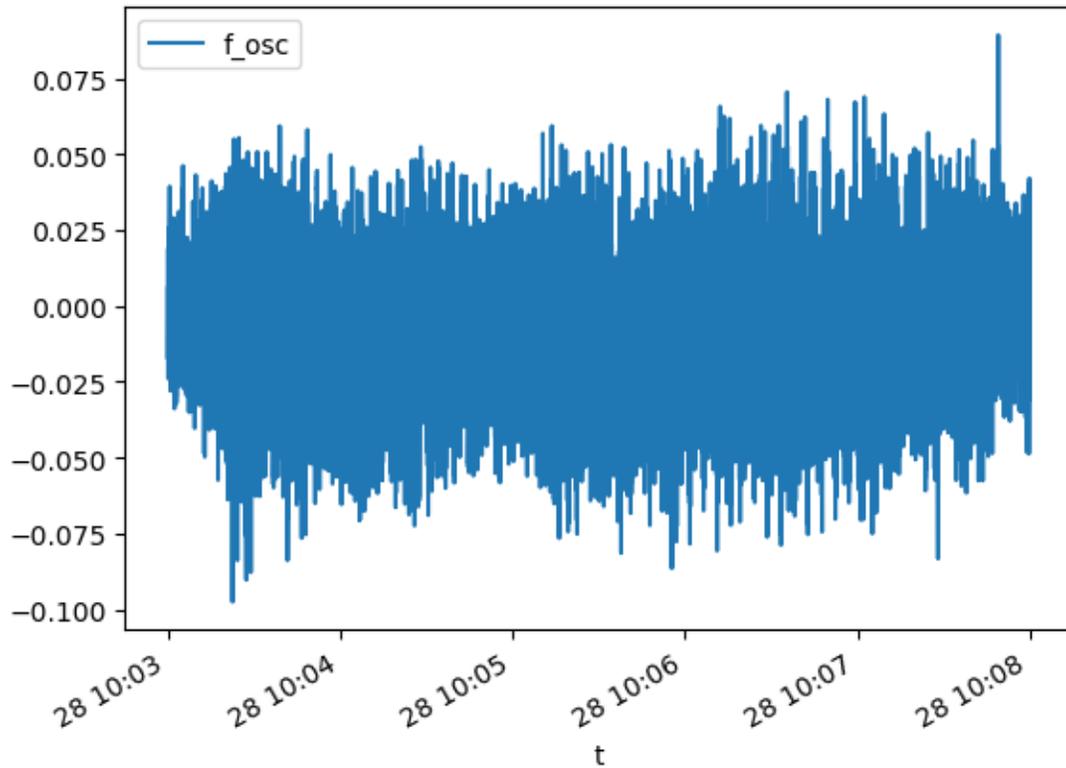
The second chart is a close-up of a few seconds and shows the repetition rate of the beats. Indeed, during the period when the oscillations are larger, the FFT bins of this signal match the location of the FFT bins of the original 1-cycle frequency. However, as expected, the values do not match because they correspond to the derivatives.



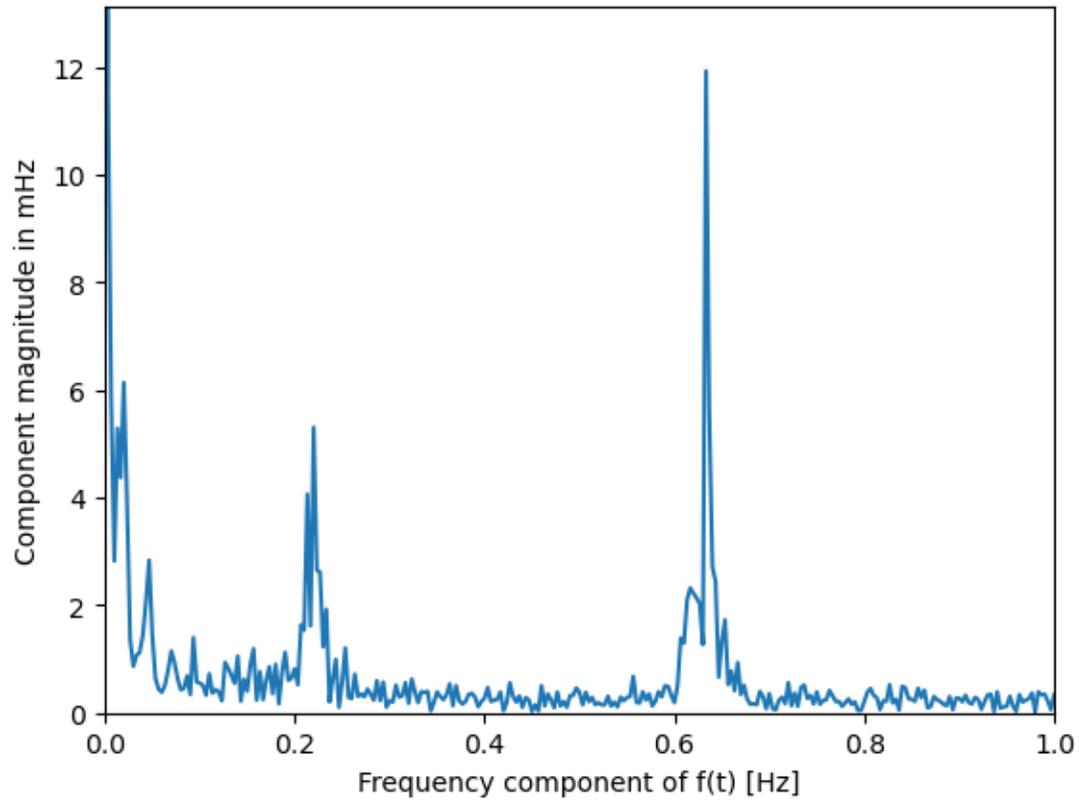
A comparison to the blackout on 28 April 2025.

Now, let's compare these oscillations with those recorded during the Spanish blackout in Seville on 28 April, which was also recorded.

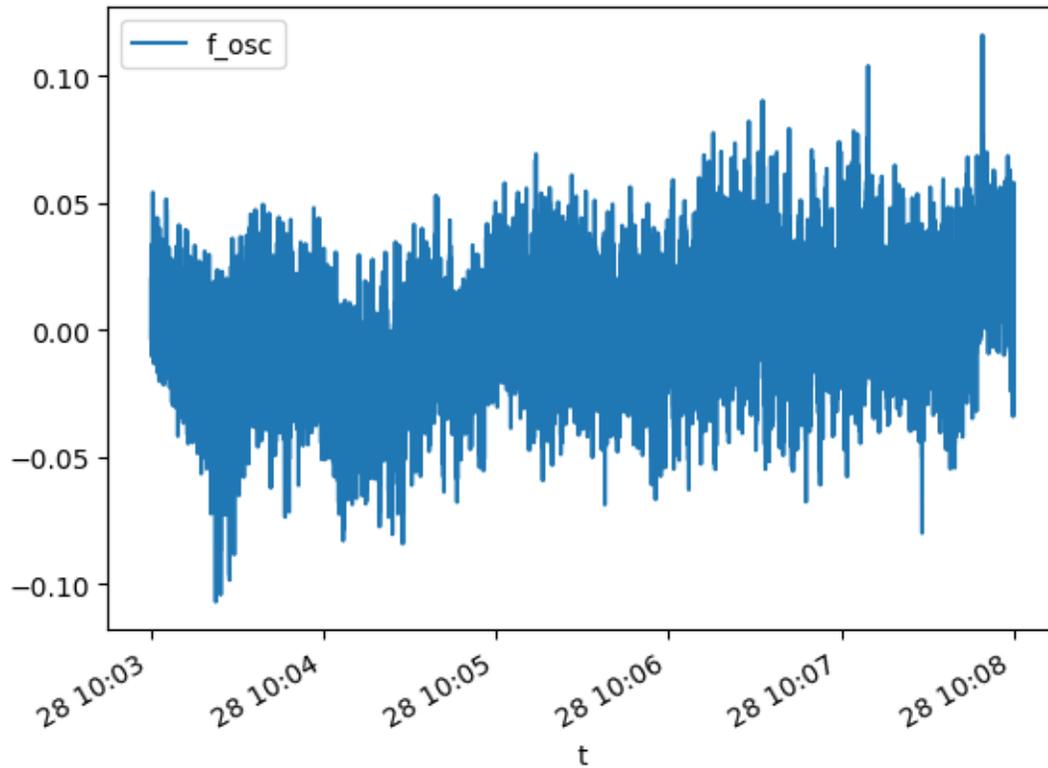
Between 10:03 and 10:08 UTC (12:03–12:08 CEST), the oscillation frequency, defined as the difference between the 1-cycle and 50-cycle values, was smaller than on 11 December.



The FFT reveals components at 0.215 and 0.635 Hz (i.e. the fundamental and third harmonic), but no other clear components.

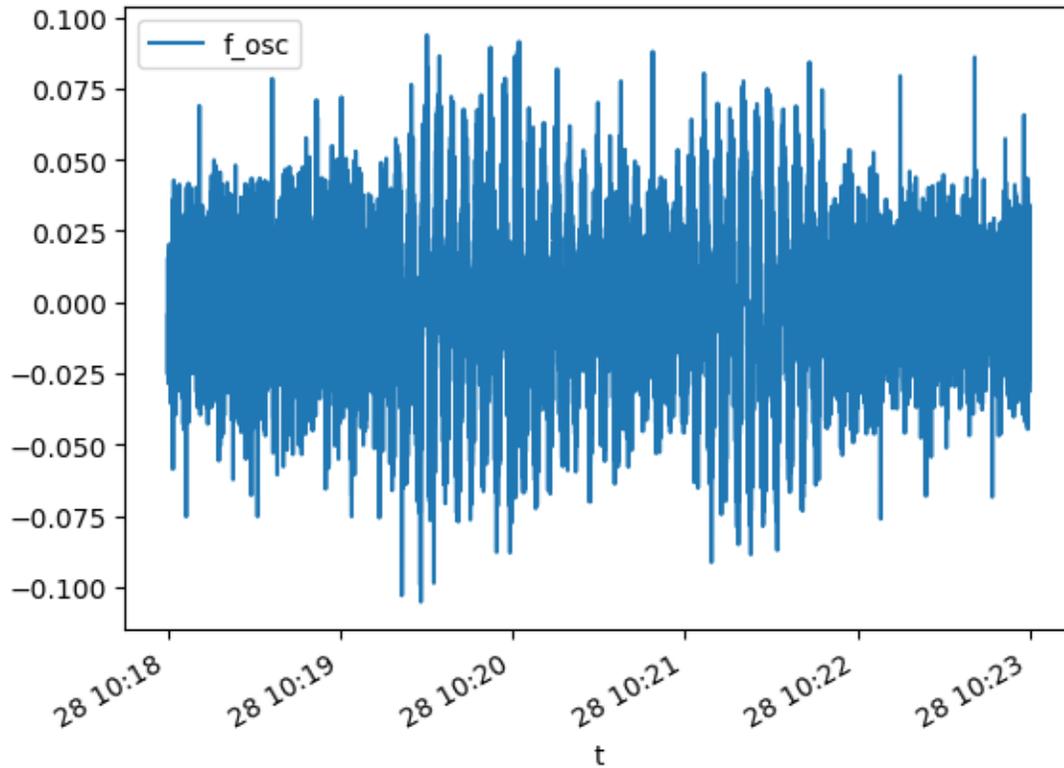


However, as the frequency was oscillating at a rate slower than once per second, the 50-cycle reference should be replaced with something even slower. Let's just take the average.

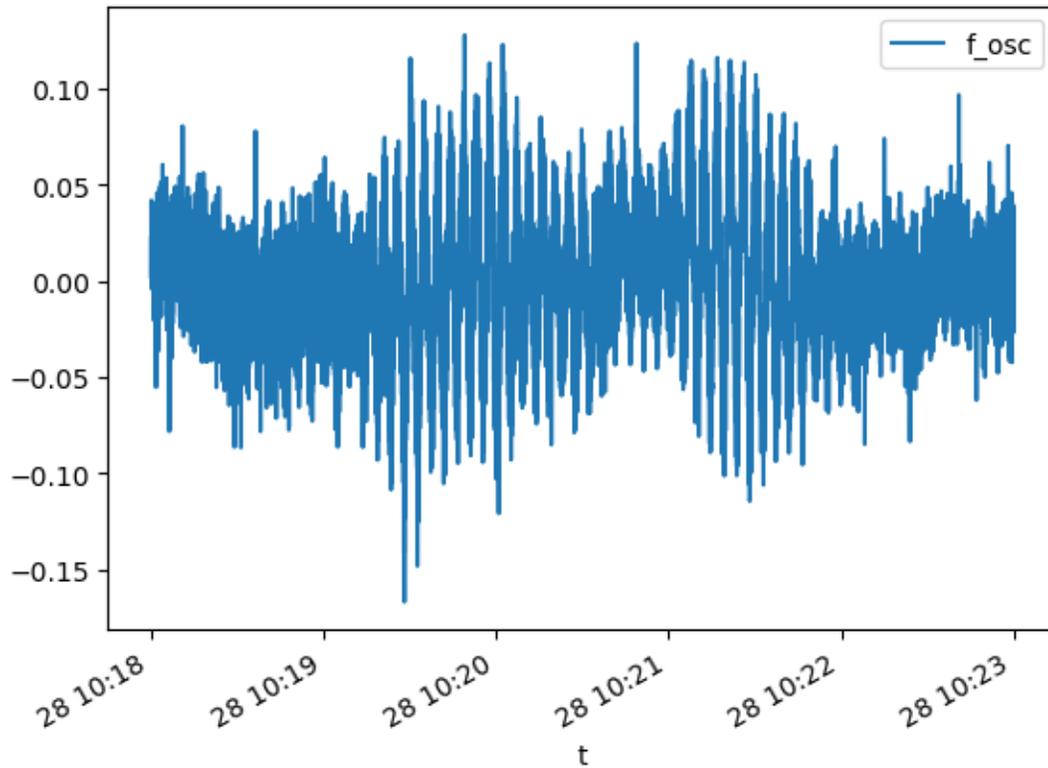


In any case, the magnitude of the oscillation was similar to that on 11 December, perhaps even smaller.

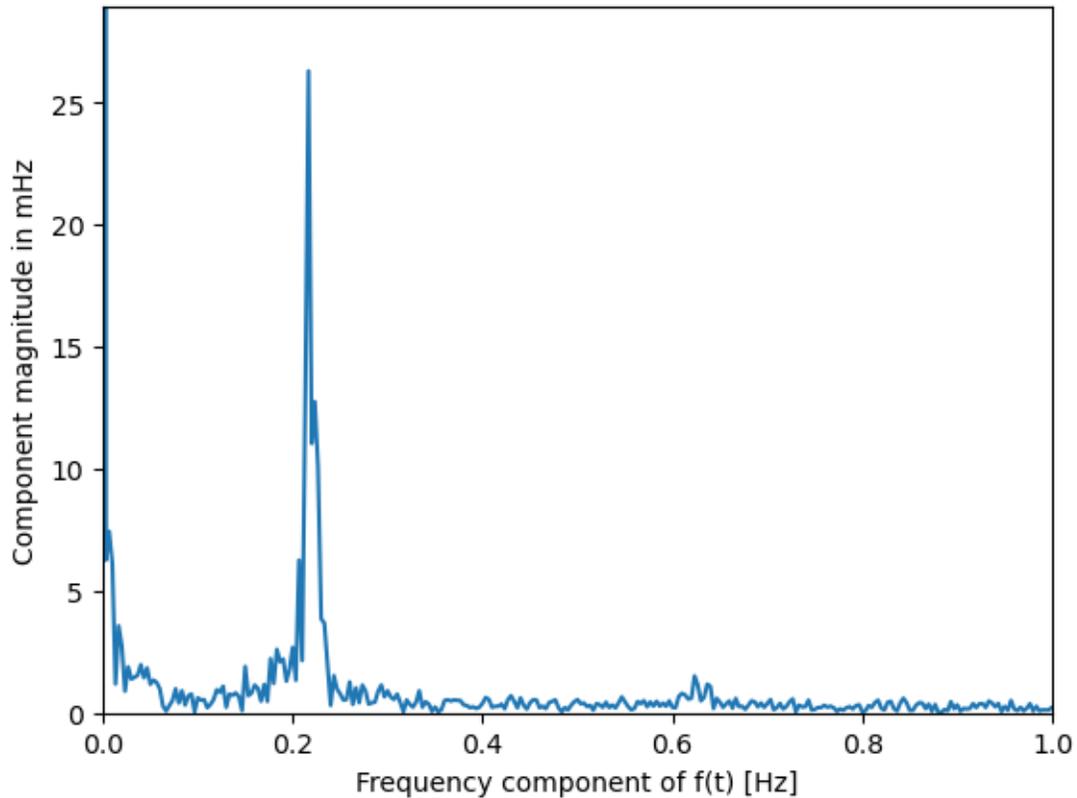
Just before the blackout, the oscillations increased in magnitude to a level similar to that on 11 December 2025.



However, if we use the average frequency as a reference point rather than the 50-cycle one, it becomes much larger at around 10:19:30 UTC (12:19:30 CEST).



An FFT shows a frequency of just 0.215 Hz, while the 0.635 Hz frequency has almost disappeared.



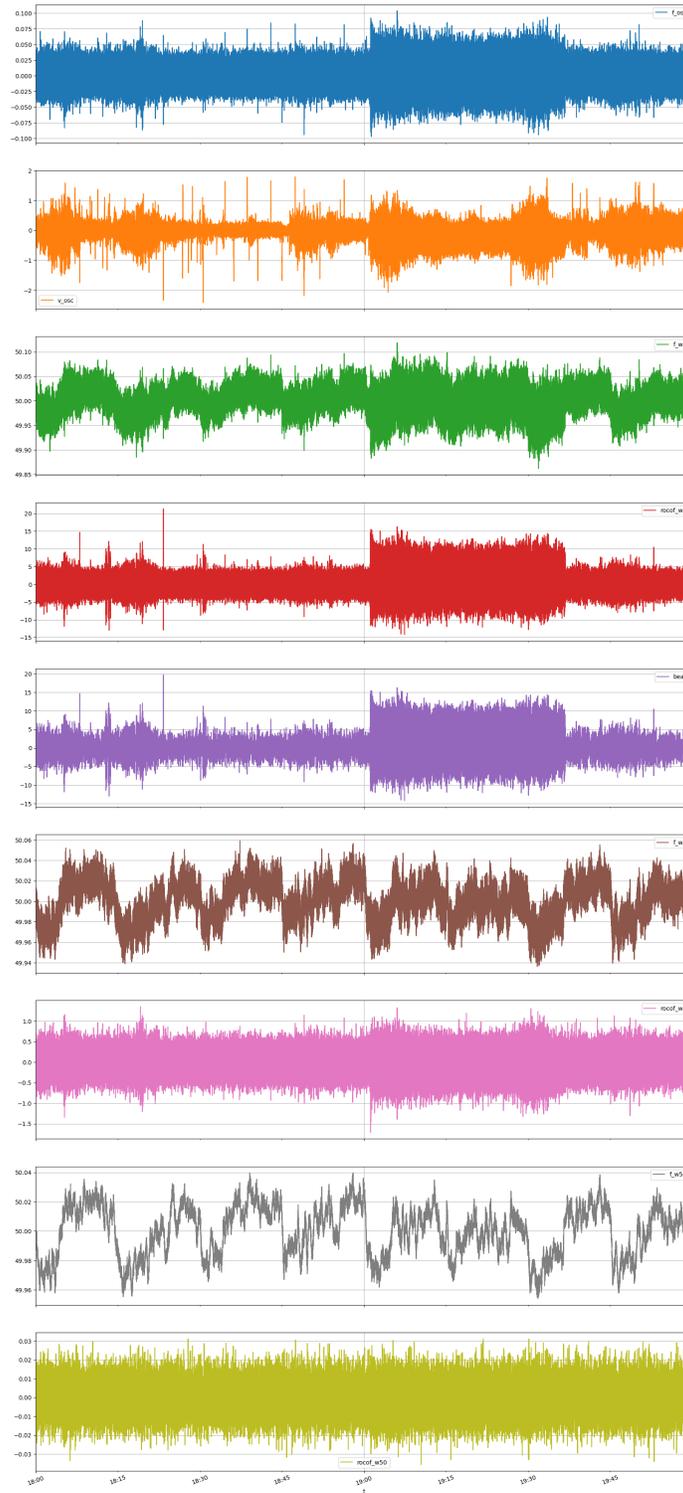
In this case, the five-cycle frequency produces the same harmonic pattern for these very low frequencies since artefacts appear above 5 Hz.

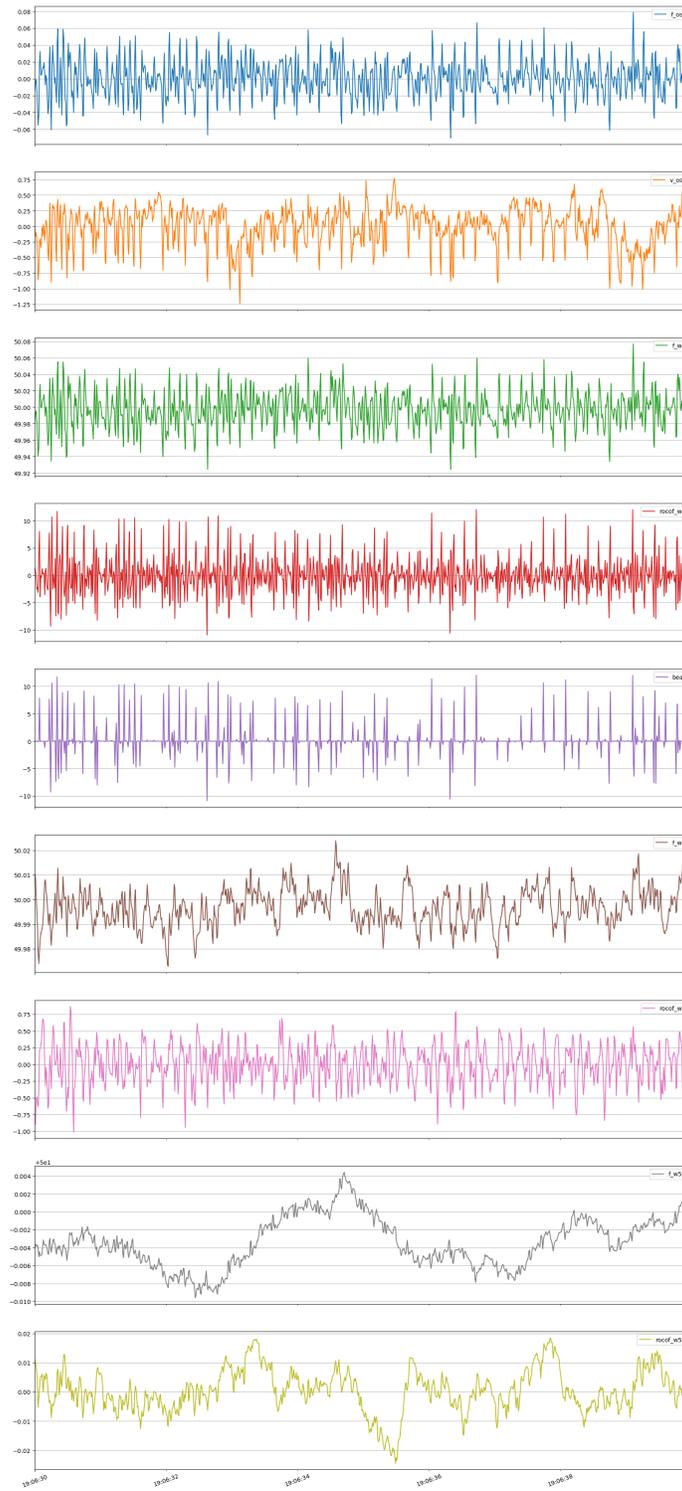
New oscillation on 29 December^{new!}

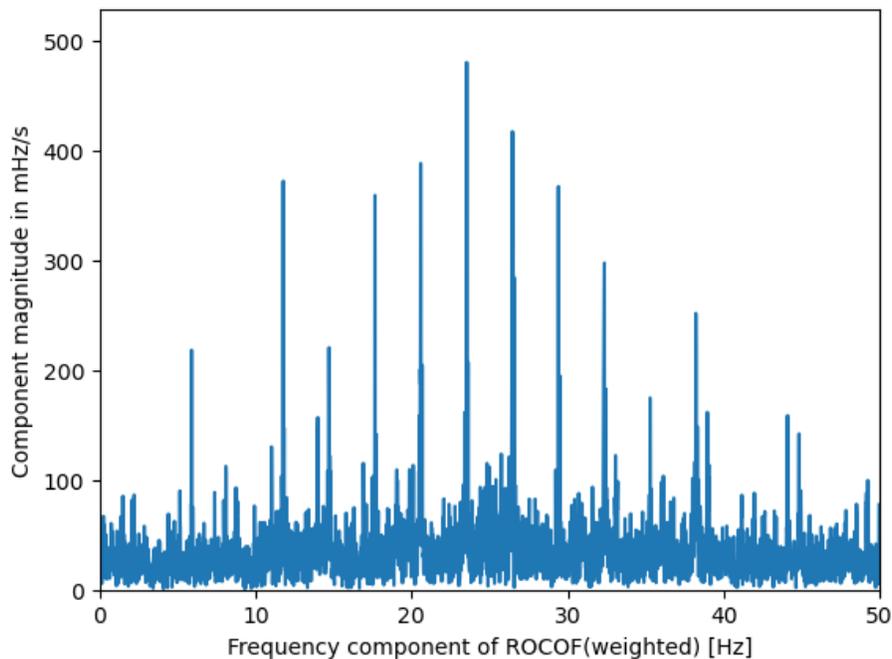
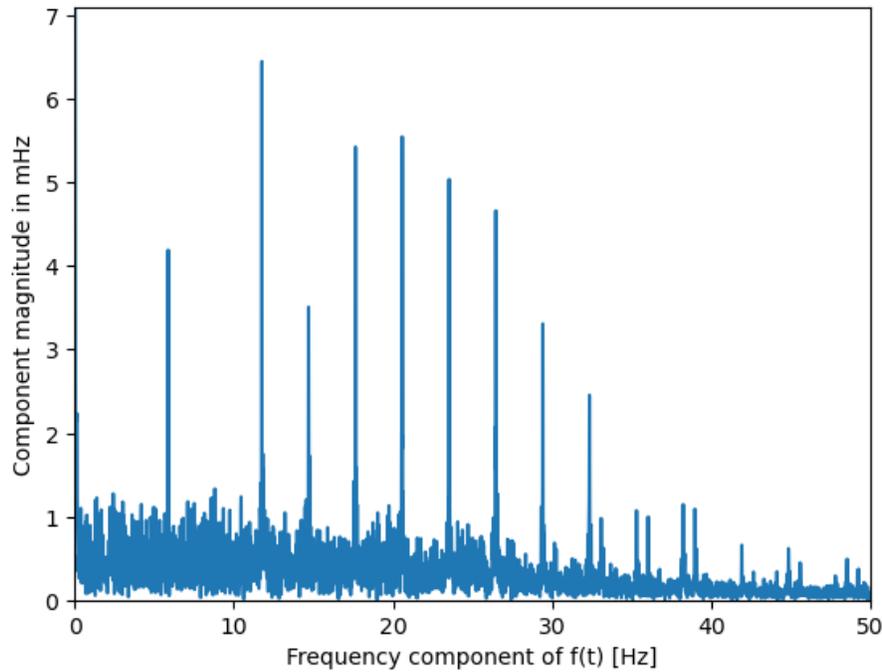
A few weeks later, new and even stronger oscillations were recorded. In this case, there is a clear 15-minute pattern, indicating that the market is driving it and that the network, or the way it is managed, is probably too weak to maintain a fairly stable frequency and voltage.

The frequency pattern is similar to the previous one in the second half, where the oscillations are larger. The FFT again shows exactly 5.88 Hz and the same separation of 2.94 Hz, pointing to the same disturbing installation.

Once again, the source cannot be a PV installation, as this occurred at night.







Source of oscillations^{new!}

The most likely source of the oscillations could be a large power electronics plant that is imperfectly synchronised with the mains via its phase-locked loop (PLL). Rather than adjusting its phase to the mains smoothly, the PLL can reach a saturation zone and oscillate around the mains phase. In such a



case, the result would resemble pulse width modulation (PWM), which produces a discrete set of frequencies around the mains frequency.

Alternatively, it is possible that the entire network and its connected elements, when considered as a complete nonlinear system, have very little damping, or even negative damping, close to the fundamental frequency. The other bins do not necessarily need to have little damping since the excitations are perceived as 1-cycle beats.

In any case, this indicates that the network is under stress, which may damage many elements, as well as other connected loads and generators.

It is also notable that the fault cannot be attributed to PV farms, since it occurred at nightfall.

Furthermore, it is highly improbable that these oscillations could be caused by a set of devices, as all their phase-locked loops (PLLs) would then oscillate at the same frequencies.

If a single PPC were the source of the oscillation, the typical delay of a fraction of a second in sending set points to the underlying devices could explain the main 5.88 Hz oscillation, but not the higher-frequency bins, which occur too quickly for this type of central control.

Conclusions ^{updated!}

It could be concluded that there are strong low-frequency oscillations in Seville (southwest Spain) that are unable to propagate to Barcelona (northeast Spain), which is around 1000 km away.

The presence of multiples of 2.94 Hz (e.g. 5.88, 8.82 and 11.76 Hz) cannot be attributed to the excitation of a single resonance frequency.

The clear 15-minute pattern seen on the second large oscillation on 29 December indicates that this is a forced oscillation.

Also, the same frequency bins are detected on both days, suggesting that the same disturbing installation is likely to be in operation.

The disturbing plant may have a PLL that is not properly configured and is reaching saturation, although this is just a hypothesis that needs to be confirmed.

The amplitude and persistence of frequency and voltage oscillations over time indicate that the network or its management is weak, even at night, which poses instability risks, especially when compared to the blackout in April.

To study subsynchronous oscillations effectively, averaging windows should be as short as possible, even when they are well above typical inter- and intra-area frequencies (e.g. 0.2 Hz). This makes 1-cycle measurements much more effective than the 5-cycle measurements usually employed by M-type PMUs.



The 1-cycle ROCOF online measurement provided by the *UNDAM*[®] *uMETER 500* offers better insight into the source and shape of the oscillations, which would otherwise require lengthy offline analysis.

The latter functionality could be used to enable fast damping triggered by the weighted ROCOF in 1 cycle and complemented by frequency deviation. This would allow damping to occur faster than if the frequency had changed significantly.

BESS installations would be ideal candidates for this enhanced control, given their intrinsic capability to behave as an energy sink.