Assessment of Recurrent Oscillation Parameters

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Abstract—Recurrent damped oscillation can occur more or less in the LV network due to different load connected. The recurrent oscillation has lower amplitude compared to other single damped oscillations events caused by e.g. lightning or switching actions. There is however a need to measure and quantify the recurrent oscillations to increase the understanding and possible consequences of these. This paper describes the phenomena and addresses different analyzing methods where ESPRIT seems to be the most promising analyzing method. In the end, the paper presents some result from a long term measurement at one site with recurrent oscillations and makes some comparisons of different analyzing methods.

Index Terms— ESPRIT, parameter estimation, power quality, power system measurements, recurrent oscillation.

I. INTRODUCTION

Damped oscillations in the LV network can occur due to several reasons. Single damped oscillation or transients, often originate from lightning or switching events. The magnitude of these single events can be relatively high and cause serious problem or malfunction to loads connected to the LV network. To make sure that equipment can withstand these damped oscillations, equipment has to undergo immunity test e.g. IEC61000-4-12 [1] and IEC61000-4-18 [2].

In LV-networks we can also find damped oscillation, which has a smaller magnitude but reoccur synchronized with the power system frequency. These recurrent damped oscillations often originate from power electronic equipment and the recurrence is typically either 2 or 6 times per cycle depending upon if it is a one or three phase load. Since these recurrent oscillations are synchronized with the power system frequency they also add to each other, if there are multiple loads of the same type connected to the same LV network. From previously performed measurement it is shown that the frequency of these recurrent oscillations is typically found in the lower kHz range [3], [4].

Since the number of power electronic equipment in the grid is increasing there is a need to quantify these recurrent oscillations in the grid. The main parameters of interest in this case are the magnitude and frequency. In order to do that analyzing tools for damped oscillations are needed. This paper first discusses damped oscillation, recurrent damped oscillations and the sources behind these in section II. In section III measurement technology for measurement used is described and in section IV different analyzing methods is discussed. Finally in section V some result from a long term measurement is shown with different analyzing methods.

II. DAMPED OSCILLATIONS

A. Non-Synchronized Damped Oscillations

Damped oscillations are in fact a diffuse phenomenon and not that well defined. There are several terms describing the same or similar type of oscillation. There are, however parameters like frequency, damping factor etc. that might differ a lot between the different terms.

• Ring wave is defined by IEC [1] as a damped oscillation, whose damping time constant is of the order of one period and a frequency at 100 kHz. IEC states that it is the most diffused phenomenon occurring in power supply networks. The source may be switching of networks and switching of reactive loads, faults and insulation break down of power supply circuits or lightning.

• Oscillatory transient is defined by IEEE [5] as a sudden, nonpower frequency change in the steady-state condition of voltage, current, or both. This includes both positive and negative polarity values. The sources of these are often referred to as switching of capacitor banks or ferroresonance. It is also stated that it may be a result of commutation of power electronics devises and the oscillatory transients that repeats several times per cycle depending upon the topology of the device.

• Damped oscillatory wave is defined by IEC and categorized into two parts. One is referred to as slow damped oscillatory wave which are caused by switching of HV busbars in open air substations. The frequency of these ranges from 100 kHz up to a few megahertz. The fast damped oscillatory wave is caused by switch- and control gear in substations or high altitude electromagnetic pulses [2].
B. Recurrent Damped Oscillations

- **Notching** is defined by IEEE as a periodic voltage disturbance caused by commutation in power electronic devices. It is stated that notches can have a wide variety of frequency content [6].
- **Repetitive damped oscillatory wave** is defined by IEC and is used to define damped oscillations from switch- and control- gear and also high altitude electromagnetic pulse. The receptivity is related to reflections of voltage front due to impedance mismatch. This type of damped oscillations is however not necessary synchronized with the power system frequency [2].

The term **recurrent oscillations** is in this paper referring to short damped oscillations, superimposed upon the sinusoidal voltage or current, which reoccurs about every 10 ms synchronized with the power system frequency.

C. Origin of recurrent oscillations

There are several sources of recurrent oscillations but two common sources are

- **Commutation notches** originate from commutations at rectifiers. At a line commutated converters this happens when the current is transferred from one diode (or valve) to another. During this event both diodes are conducting creating almost a short circuit which in its turn affects the voltage and on the grid side, depending upon the grid parameters, this will show up as periodically damped oscillation or recurrent oscillations.
- **Zero-crossing distortion** or cross over distortion originates from active power factor correction circuits in loads. The source of these recurrent oscillations is that the load is slightly capacitive and the current reach zero before the voltage. The current can’t flow in the opposite direction of the diodes and this cause a pause on input current until the voltage reaches zero. There will also be an instantaneous current step generating a zero-crossing distortion on the AC side of the inverter. The phenomenon is though more prominent in higher frequency systems like aircrafts or submarines but still visible in power systems at 50 or 60 Hz [7].

Note that these are just some examples of recurrent oscillations. They are however mostly caused by loads and therefore not visible at all locations. The magnitude and frequency of recurrent oscillations is most likely depending upon the load but also the grid parameters i.e. grid impedance. There are also sites where these are not as prominent. Below in Fig. 1 are two examples from two sites showing recurrent oscillations in the voltage waveform.

III. Measurement of Recurrent Oscillation

A. Measurement specification

Measurement of waveform distortion in standards is typically divided into different frequency ranges. The harmonic range covers from DC to 2 or 3 kHz and is well covered by IEC 61000-4-30. Measurement in the range from 2 kHz up to 9 kHz is somewhat less described but there are some description in informative annexes of IEC 61000-4-30 and IEC 61000-4-7. From 9 kHz and upward measurement of the radio service protection is also described by CISPR 16 series. The CISPER method is though quite different when the method is mostly aimed at test laboratory measurements on EUT’s. It differ in several ways but these type of measurements are performed with the use of spectrum analyzers, and time domain measurements is not prescribed and e.g. voltage measurement is taken between phase and earth and not phase and neutral etc.

As mentioned above is the frequency of recurrent oscillations in the lower kHz range and often falls into the 2 to 9 kHz measurement range.

B. Need of filtering

In power system, the magnitude of both the harmonics and the supra harmonics components is typically decreasing with frequency and has the lowest magnitude in the supra harmonic range. In order to measure these low magnitudes, superimposed upon the power system fundamental voltage, there is a need of either an analogue filter to reduce the power system frequency voltage or to increase the number of bits used by the A/D converter. For that reason both IEC standards mentioned above prescribes the use of a band-pass filter where the lower band-stop are used to attenuate the power system frequency and upper band-stop section is for antialiasing purposes. For analyzing recurrent oscillations there is also a need to filter of the power system frequency and this also hold for the harmonic range where such requirement is not necessary. There is however drawbacks with using filter on signals and can be especially delicate on damped oscillations or transient which is necessary to be aware of.

During the course of time the power engineering group at LTU has used different types of filter. Both analog passive
and active filter has been used. Passive filters have the benefit of not adding any noise to the signal but on the other hand it has damping factor in the pass-band which is often caused by a low insert impedance of the filter. Active, analogue filter has also been used but these types of filter has a limited input amplitude range. This is problematic due to the fact that signals in this range can differ a lot between different sites and also over time. Active filter may also introduce unwanted noise to the measurement. A benefit is though that it is easier to achieve a high input impedance.

Below, in Fig. 2, is an example of both a digital (top) and passive analogue (bottom) filtered waveform shown of the measured signal in the top figure of Fig. 1 above. In this case both measurements (unfiltered and analogue filtered) where measured with 12 bits vertical resolution and 10 MS/s time resolution. The analogue filter used in this case is a 2\textsuperscript{nd} order high pass RC filter and the digital filter is also a 2\textsuperscript{nd} order high-pass butter-worth filter. As can be seen the result from both filters are similar but there are some deviation. The peak amplitude of the recurrent oscillations is though affected differently by the different filters and this indicates that the filtering will affect the recurrent oscillations.

**Figure 2.** Digitally HP filtered voltage waveform (top) and analogue filtered waveform (bottom) with recurrent oscillation visible every 10 ms

Fig. 3 below shows a close-up of one of the recurrent oscillation shown in Fig. 2 above. In this case the peak amplitude is about 4.5 V and the frequency is about 13 kHz.

**Figure 3.** 3 ms sub-window of the analogue filtered recurrent oscillation shown in Fig. 2 above

IV. Methods of Analysing Variation of Recurrent Oscillations

As mention above, these recurrent oscillations is a damped sinusoidal oscillation. When analyzing these variations it is important to know what parameters that is of interest, if it is peak value, frequency, damping factor or phase or a combination. The commonly used tool of spectrum analysis is the use of a DFT but this method is though not suitable for analyzing these types of damped oscillations since recurrent oscillation a discontinuous signal.

A. Peakvalue

If only the peak value is of interest is the simplest way of getting estimation on the magnitude of the damped oscillation is to filter the 200 ms waveform and the take analyze the peak value of each window. This is a simple and robust analyzing method of the amplitude but as discussed above the use of a filter may however have an impact on the result and this method does not disclose anything about the frequency, damping factor or phase.

B. ESPRIT

Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT), is a powerful estimation tool that can be used to estimate damped oscillatory waveforms [8],[9]. The recurrent oscillation needs however to be pretreated by both a high pass filter and also a choice of sub-window. The effects of the filter is mainly on the magnitude but there is also a risk depending upon the frequency that phase information is also affected.

Below, in Fig. 4 is some examples of synthesized 2 ms signal, estimated by ESPRIT with different starting points. As can be seen is the estimation error (top figure) low on all parameters when the sub-window start exactly when the damped oscillation starts. If the sub-window of the damped oscillation is taken too early (as shown in the middle graph of Fig. 4) the error of all parameters is increasing. If the sub-window is taken too late (as shown in the bottom graph of Fig. 4) only the error of the magnitude and phase are affected while the error of frequency and damping is still low.

<table>
<thead>
<tr>
<th>Synthesized signal</th>
<th>Magnitude</th>
<th>Frequency</th>
<th>Damping</th>
<th>Phase</th>
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</thead>
<tbody>
<tr>
<td>Estimated parameter</td>
<td>10</td>
<td>2000</td>
<td>2000</td>
<td>-90</td>
</tr>
<tr>
<td>Error (%)</td>
<td>6.8992%</td>
<td>0.1739%</td>
<td>0.5346%</td>
<td>6.9479%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Synthesized signal</th>
<th>Magnitude</th>
<th>Frequency</th>
<th>Damping</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated parameter</td>
<td>4.7308</td>
<td>1.5076x10(^3)</td>
<td>3.0030x10(^3)</td>
<td>-106.4589</td>
</tr>
<tr>
<td>Error (%)</td>
<td>92.0%</td>
<td>4.622%</td>
<td>7.4807%</td>
<td>20.5219%</td>
</tr>
</tbody>
</table>
Some trials with a synthetic signal was also carried out on both heavy damped oscillations and a short subwindow as shown in Fig. 5 below. As can be seen can ESPRIT estimate a heavy damped oscillation with good accuracy. There is however a limit but a more damped oscillation then shown below is probably not of interest. From this test it can also be seen that it can estimate the parameters with good accuracy on very short sub-windows. Test not shown here reveals that it maintain a good accuracy down to ¼ of a cycle.

From this trial with a synthetic signal and ESPRIT we can conclude that it is important to choose the right sub-window which requires pre-knowledge about the recurrent oscillation. The ESPRIT estimation seems estimate correctly even though the sub-window is taken rather late or is heavily damped or just a short sub-window.

V. EXAMPLE OF RESULT FROM A LONG TERM MEASUREMENT

Several longterm measurements has been carried out at locations with recurrent oscillation and the result from one of these measurement over a week is being analyzed here. During the timeperiod, 200 ms window where taken every minute resulting in about 10,000 windows. The sampling rate of the measurement was 10 MS/s and the instrument had a 12-bits amplitude resolution. An analogue passive bandpass filter was used and also, not shown here, unfiltered waveforms where taken.

Fig. 7, below shows the result of the magnitude variations of the recurrent oscillation at the site, analyzed in four different ways. The upper graph shows the result of the peak magnitude of each filtered 200 ms window during the week. The peakvalues of the filtered waveform ranges from about 8 to 15 volt and the average is 11.22 V during the measured period. The second graph from the top shows the result when using ESPRIT on the same data. In this analyze a 3 ms subwindow starting 0.5 ms before the peak of the measured recurrent oscillation is analyzed. When using the ESPRIT in this way the estimated magnitude of the recurrent oscillation drops down to be between 0 and 5 V and the average voltage over the whole period is 2.76 V. When comparing the magnitude of peakvalues with the estimated values the magnitude pattern is though about the same through out the whole measurement. The next graph, third from the top, is showing the estimated magnitude when a 3 ms subwindow starting at the peak of the recurrent oscillation is used. Compared with the peakvalue (top graph) it also shows a similar pattern as the peakvalues but the deviation is larger, from less than 1 V to 12 V. The estimated values are also more noisy which comes from the fact that the recurrent oscillations is not so clean every measured sub-window. The average voltage with this method is 5.96 V. The last graph (bottom) shows the resulting estimated magnitude when an adaptive start of the window is used. I.e. when the first zero-crossing of the damped oscillation is used as a starting point of the 3 ms subwindow. This graph shows also a somewhat noisy pattern, same as when the peak is representing the start of the subwindow (third from the top), but the estimated peak magnitudes reaches in this case 15 volt and the average voltage is 5.34 V.
Now and then the recurrent oscillations may consist of other components that makes them more difficult to estimate the right parameters of the recurrent oscillation. Below, in Fig. 8, is an example from the measurement shown above where it happens to be two consecutive recurrent oscillations. The peak value of the first damped oscillation is about 9 V (upper graph of Fig. 8) and when applying the ESPRIT it will give a magnitude of 0 volt (lower graph of Fig. 8).

As can be seen from Fig. 6 there are estimations that appears not to deviate too much between peak values (top) and e.g. ESPRIT estimations from a window starting at the peak (shown in third graph from the top in Fig. 6). Fig. 8 below shows one of these examples where the measured sub-window is shown in the top graph and the estimated signal is reproduced in the lower graph of Fig. 8.

Since test with a synthetic signal in section IV shows that estimations can be done on a short sub-window, a trial with this was carried out with sub-windows starting at the peak of the recurrent oscillations. Fig. 9 shows the result of 1 ms sub-window taken at the top and a 0.5 ms sub-window at the bottom. When shortening the sub-window to 1 ms it seems like ESPRIT is estimating the magnitude accurate since there is less variation during the measured time period. In the 1 ms estimation (top graph of Fig. 9) the variations is still between less than 1 and 15 V but the average value increases to 10.46 V compared with the 3 ms sub-window analyse shown in Fig. 6 above. The result when shortening the sub-window even more, (0.5 ms in the lower graph of Fig. 9) shows that ESPRIT can estimate the magnitude even better. The average during this estimation is 11.71 V which is close to the average of the peak values in Fig. 6 above.

Below in, Fig. 11 the frequency estimation through the three different ways is shown. The average frequency the whole period is 1.73 kHz, 1.57 kHz and 1.66 kHz. The frequency estimation seems to be fairly similar between the different ways of picking out the sub-window. This indicates that the choice of sub-window is not affecting the error in frequency that much and this is also what indicated above in Section IV.
consecutive recurrent oscillations which means that one desire to keep the sub-window as short as possible around the recurrent oscillation. When using a DFT, a short window will affect the frequency resolution which is not desired. The result though from Fig. 11 is that it seems to perceive the correct frequency but the frequency resolution is much lower compared with the use of ESPRIT.

Both time and frequency resolution can be enhanced with sliding window and zero-padding technique and this was not tried here. This method does not in any way improve frequency resolution, it is adding more points to the frequency domain.

VI. CONCLUSION

There is a lack of a clear definition on damped sinusoidal oscillations in LV power systems. One reason to this might be a large diversity of sources, appearance and effects. There are also difficulties analyzing these types of waveform distortions which make it difficult to get the correct amplitude of a recurrent oscillation. It doesn’t matter which analyzing method use, a pre-filtering is needed to analyze recurrent oscillations but it is likely that this may also affect the magnitude of the oscillation and one has to be aware of this effect. Pre-knowledge of the frequency and magnitude of the recurrent oscillation may be needed to adjust the filter in order to get the correct magnitude.

Analyzes of long-term measurement has been carried out with three different methods. Just filtering and getting the peak-value is maybe the easiest way but there will not be any more information other parameters, i.e. about frequency, damping factor etc. A trial with DFT was also carried out but it suffers from time-frequency resolution constraints and therefore it is not so exact even though it works. ESPRIT seems to be most promising but there are some things to watch out for.

The accuracy of ESPRIT depends among all on the choice of sub-window, both starting point and length. To get accurate parameter estimation it is important to either start at the zero-crossing or the peak of the recurrent oscillation. A sub-window start before the start of the recurrent oscillation will quickly lead to large errors on all parameters while a late start will only affect the error of the phase and magnitude while it still can estimate the frequency and damping factor with good accuracy. ESPRIT can handle both heavily damped and short recurrent oscillation. Since the recurrent oscillations in the long term measurement shown in this paper can contain several in an short duration the capability to estimate with a short sub-window was utilized. The result from this method showed good conformance of the magnitude with the peak value analysis. From the test with different choices of sub-windows we can see that the estimated frequency does not change that much which means that the ESPRIT estimation of frequency is reliable.

ACKNOWLEDGMENT

The author gratefully acknowledges I. Y. H. Gu for the contributions with the ESPRIT algorithm.

REFERENCES