Frequency identification and Virtual PLL

Frequency domain analysis is often used to analyse, describe and rate systems and their interaction with surrounding equipment. It transforms a time signal into a spectrum. For example, loads connected to public grids have to fulfil a number of criteria, many of them defined in the so-called frequency domain.

Mathematically, this frequency domain can be reached by Fourier expansion, Fourier series calculation, Laplace transform and others. Basically, the time signal to be transformed and analysed has to be known from minus infinity to infinity – which is certainly not a very practical demand.

Because of this, for signal analysis with regard to the analysis, description and rating of equipment a time interval, called base interval T_{B}, is used (Fig. 1). These time intervals queue in positive and negative time-axis, forming an artificially periodic signal. If the period of the signal under analysis matches the duration of the base interval – or is an integer fraction of the base interval – analysis is straightforward and does not present obvious or severe problems.

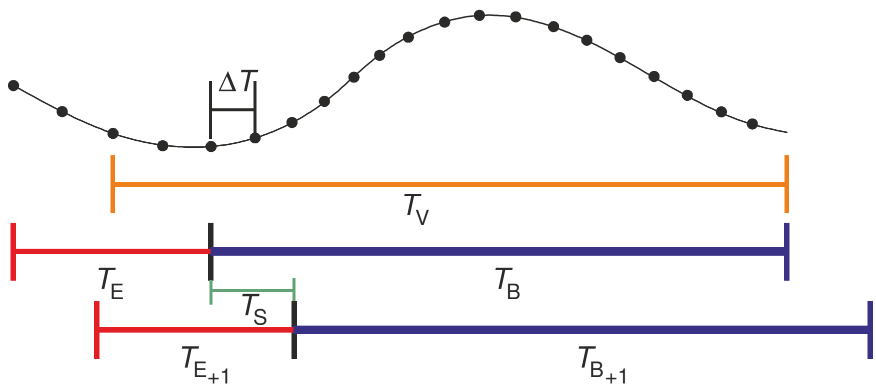

Fig. 1: Definition of time intervals

A further practical demand is to use a finite number of data (with a given resolution also for the values selected). The resulting signal becomes value-discrete and time-discrete (with a sampling-time interval ΔT). In this way digital computers can quite easily transform a time signal into the frequency domain - giving seemingly easily interpretable results.

In practical applications, discrete Fourier transform (DFT) and fast Fourier transform (FFT) automatically incorporate the above mentioned aspects. Virtually all frequency domain analysis, at least in the area of electrical power engineering and associated domains, is done using one of these methods for transformation.

Several problems arise - with several solutions being available for their mitigation:

- The restricted resolution of the values leads to quantisation noise - which can be mitigated by filtering and, if need be, an increased resolution. Such noise results also if transducers are utilized to sample physical quantities for analysis.
- The number of sampled values per time interval can be too small for the intended analysis. Zero-padding (inserting zero values as artificially created data) and an increased number of sampled values could mitigate this problem.

- The period of the actual signal could not match the selected interval. In this case "frequency leakage" occurs - which is usually mitigated by applying selected so-called "window functions". Also, phased-lock-loop technology (PLL) is used to tune the time instants for sampling values to the period of the signal.

Careful layout of the data acquisition system removes the first two problems stated in a way sufficient for practical applications. In simple cases, where the signal to be analysed is truly periodic, PLL also solves the third problem. The use of power-electronic converters and also the use of various frequencies for energy transmission (16.7 Hz, 50 Hz, 60 Hz and 400 Hz being the most prominent ones), combined with speed-variable AC drives introducing quasi-arbitrary frequencies of operation make it difficult, in many cases even impossible, to select an appropriate time interval as basis of frequency-domain analysis for a signal. The remaining straightforward method to cope is the use of window functions - which alter the frequency-domain results in a way making sensible analysis in the areas of electrical power engineering, power-electronics, grids and drive systems difficult or even impossible.

With regard to this, frequency identification was introduced as a tool [1, 2, 3], allowing off-line analysis of each sinusoidal component within a signal giving its amplitude, phase and frequency. These components can no longer be seen as harmonics, as their individual frequency is no longer linked to the time interval used as basis for the frequency-domain analysis.

The need for such analysis is special to the domain of electrical power systems. Under usual quasi-steady-state conditions, signals consist of clearly defined sinusoidal functions, each of these with a certain technical source, a sort of “reason for existing”, which helps to analyse the functionality and tolerability of the system which causes the signal. In case of speech or image processing, totally different demands exist – making the elaborate methods known in these domains practically unusable.

If on-line or real-time analysis is needed, the frequency identification is usually too slow. Modifications of the basic principle resolve the problem, leading to fast and accurate analysis. In the following, several options are presented - which can be combined in order to tune the method to the application at hand.

Basically, with a sequence of time intervals being recorded, one round of frequency identification can be done for each recorded interval (and not the whole multi-round identification process. In this way, the effort per interval is considerably reduced – still retaining the need to identify many sinusoidal components individually.

Most signals do not contain arbitrary sinusoidal functions, but several sets of harmonics with different base frequencies. In case of AC drives fed by power electronic from a 50 Hz grid, one set of harmonics will be associated with the 50 Hz grid frequency. A second set could result from the stator frequency applied to the AC motor. A third set of harmonics results from the switching of the inverter. Of course, modulation products have to be expected.

In such a case, a PLL can be used to tune the base interval and the sampling of measured values to the actual frequency of the 50 Hz grid, eliminating frequency leakage for all directly associated harmonics. These clearly known harmonics need no identification. They can be removed from the spectrum as known from frequency identification. Already here a simple version of Virtual PLL could be applied if the sampling-time interval ΔT itself cannot be modified. In such a case the base interval would not be perfect – but still acceptable, if the sampling-time interval is sufficiently short.

Within the remaining spectrum, the largest component can be identified as known from frequency identification. The identified frequency of this component defines an associated virtual base interval – with a statistical inaccuracy of half of the time step between two sampled values. No "real" base interval is created by this - because the "real" base interval is defined by the "real" PLL. Therefore the method described here is called virtual PLL (ViPLL). A further DFT or FFT on the basis of the virtual base interval now gives the exact amplitude, phase and frequency of all harmonics associated with the respective basic effect, e.g. the stator frequency of the AC machine or the switching frequency of the converter. Again, these virtual harmonics can be removed from the spectrum.

With properly defined signal acquisition, providing an extended interval T_{E} for analysis, the virtual base interval T_{V} can not only be shorter than the main base interval T_{B}, but also longer. This option is of interest if the ViPLL is expected to lock on a frequency below the fundamental frequency associated with the main base interval.

Should further sets of harmonics exist, they can also be identified and removed in the above mentioned way by introducing further ViPLL base intervals.

The virtual PLL usually does not reach the quality of a real PLL. If, however, the time step from sample to sample is small enough, the accuracy is sufficient - and the result far more easy to interpret than in case of window functions. However, as known from frequency identification [1, 2], window functions are part of the identification procedure and enhance ease of operation and quality of results.

One more example for several sets of individual harmonic series overlapping within a signal can be found in case of static converters linking 50-Hz public grid and the 16.7-Hz railway grid. Consequently, also faults connecting two grids with different frequency of operation (for example the two just mentioned) can be analysed well with ViPLL methodology.

In any case, sinusoidal signals with frequencies clearly not related to any of the harmonic sources discussed above can remain within the signal. Ripple control signals in public grids could be an example, also track circuit frequencies in railway grid applications. Such remaining harmonics can still be identified in the step-wise approach (one step per recorded base interval) described above.

While the straightforward approach would be to record one base interval of data after the other, an overlap (moving the base interval by a fraction of its duration) is also applicable. In this case the interval per step T_{S} is smaller than the main base interval T_{B}. The larger the overlap (the shorter the interval per step T_{S}), the faster the reaction – and the more demanding the requirements on computational power.

In case of FPGA with their highly parallel structure the parallel implementation of some of the above mentioned methods can further reduce calculation time and facilitate real-time implementation. Quasi-parallel implementation is also reached by multi-threading on multi-core CPU systems.

[1] Staudt, V.; Wiesemann, J.: Identification of Sinusoidal Functions Contained in a Signal. 7th International Conference on Harmonics and Quality of Power (ICHQP VII), 1996, Las Vegas, pp. 375- 380

[2] Sonnenschein, M.; Staudt, V.: Evaluation of a shunt active filter using frequency identification. 8th International Conference on Harmonics and Quality of Power (ICHQP VIII), Oct. 1998, Athens, pp. 617-622

[3] Peretto, L.; Staudt, V.; Sasdelli, R.; Tinarelli, R.: Performance Comparison of a Deterministic and a Statistical Approach for the Analysis of Multi-Tone Signals. IEEE Symposium on dignostics for electrical machines, power electronics and drives, SDEMPED, Grado, 2001, S. 325-331