ON-LINE 2 TO 150 KHZ GRID IMPEDANCE METER

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ABSTRACT

Active In-feed Converters (AIC) generate harmonics with frequencies up to 100 kHz resulting in power losses over the distribution lines, transformers and consumer loads, and interferences with control signals. The value of the harmonic voltage at an In-plant Point of Coupling (IPC) depends on the grid impedance at the harmonic frequency. As the spectral impedance of a distribution grid section cannot be estimated by calculation, it has to be measured. This paper presents the "on-line" grid impedance meter designed for spectral impedance measurements of low voltage distribution grids over the frequency range between 2 and 150 kHz. A useful application of spectral grid impedance measurement is presented at the end of this paper, with the analysis of interferences between two photovoltaic inverters.

INTRODUCTION

Active Infeed Converters (AIC) are necessary to feed energy from solar panels and wind turbines, battery stacks or braking electrical motors into the local distribution grid. Following the latest incentives for higher energy harvesting from renewable resources and for higher energy efficiency in processes, Active Infeed Converters are rapidly increasing in popularity. Static energy conversion offers numerous advantages in terms of cost, flexibility and efficiency. There is, however, a flipside of the coin: as power electronic equipment generates perturbations in form of harmonics rejected to the grid, we are facing new power quality issues as well as EMC interferences between converters and control signals transmitted over the supply lines (PLC). Due to the latest progress in technology, the harmonics generated by converters have moved from a very low frequency range to tenths of kHz. Until now EMC standards have been successful in limiting interferences in the frequency domain below 2 kHz. The classical approach has been to set limits for harmonics emission of a single piece of equipment and to define immunity for the same piece of equipment to a higher interference level, corresponding to the emission of numerous devices. To simplify, tests were carried out under specific laboratory conditions; statistics and experiments confirmed that things would go fine in the real world. With the increase of frequency ranges and of the density of electronic equipment connected to the same grid, the complexity of electromagnetic compatibility has taken a new dimension. The 'out of my garden' kind of philosophy, i.e. building a fence or rather an EMC filter around one's equipment and hoping that the 'noise' generated by others will not come over, has reached its limits: numerous EMC filters based on inductors and capacitors connected to the same IPC tend to resonate, resulting in the weakening of the 'defense' system. The costs of EMC filters and inherent thermal losses represent nowadays a burden for the converter industry. Adding the new trend of using Power Line Communication for the orchestration of the Smart Grid, we understand that it is time for a more systemic approach. [1]

An interesting approach would be a systematic matching of the harmonics generated by specific AIC equipment with the grid impedance at its point of connection to the grid, and this over the whole frequency range where harmonics could be present. The scope of this approach is to minimize the losses over the lines and EMC filters connected to this point and to reduce filters in size whenever this is possible.
Due to the complexity of the low-voltage distribution grid and in most cases the complete lack of knowledge of the line layout and of devices connected, it is not possible to estimate the spectral grid impedance by calculation only. The only efficient and accurate way is to measure it.
Various solutions for the measurement of spectral grid impedance were proposed in the literature, sometimes resulting in commercialized equipment. [2]-[5] However, at the start of our project, none was covering the whole frequency range between 2 and 150 kHz, which is in the scope of many standardization projects. This situation motivated us to develop the equipment described in this paper. [6]

TECHNICAL BACKGROUND:

The grid impedance at the In-plant Point of Coupling (IPC) of an AIC to the power supply system is the resulting impedance consisting of the supply impedance and the supply-side filter impedances of electronic devices connected to this point.

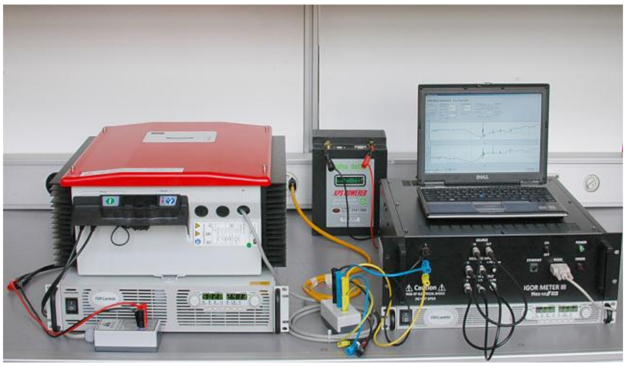

Fig. 1. Wideband grid impedance measurement set-up

The supply impedance is given by line and transformer impedances and is usually assumed to be inductive in the lower part of the frequency spectrum. The supply side filters for AIC are designed to offer a short-circuit path inside the filter for high frequency oscillations and to block their way towards the grid. The most efficient and most commonly used filters are based on an LCL circuit in a T-structure. For inverters controlled with a constant switching frequency, damped trapped filters might be applied. Small power rated converters or electronic appliances are usually equipped with CLC filters with a PI-structure. Passive filter circuits based on capacitors and inductances will only produce resonance phenomena at specific frequencies.

In case of a serial resonance, the resulting impedance will be extremely low. In an opposite manner, resulting impedance in case of a parallel resonance is high. An example is given in figure 2, with the calculated spectral impedance of a typical supply side CLC filter for an electronic lighting ballast:

$$Z(j\omega) = \frac{(R - RLC_2 \cdot \omega^2) + j \cdot \omega L}{(1 + LC_1 \cdot \omega^2) + j \cdot R(C_1 + C_2 + LC_1 C_2 \omega^2)}$$

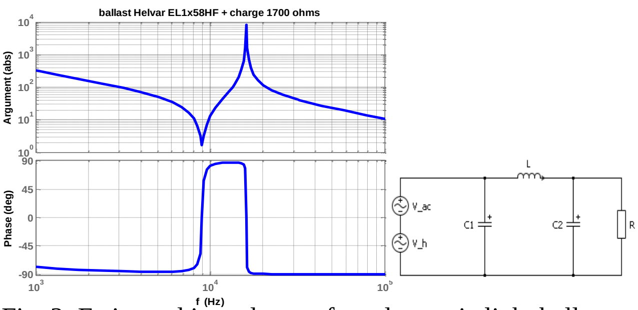

Fig. 2: Estimated impedance of an electronic light ballast

Depending on the length and size of the connecting lines, the supply side impedance seen from the point of common connection will be greatly influenced by the line filter impedances of electronic loads connected to that IPC.

The resulting grid impedance cannot be assumed to be constant over a wide frequency spectrum any more. It can actually vary dramatically from the value of the line impedance at the power frequency.

In order to illustrate the impact of the grid impedance on the transmission efficiency of harmonic perturbations over the electrical distribution system, we will consider the example of a voltage source converter (VSC) controlled with a pulse width modulation at constant frequency. The corresponding simplified circuit diagram is represented in figure 3.

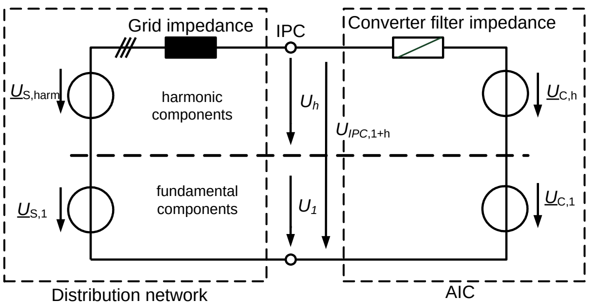

Fig. 3.: Equivalent circuit with VSC and Zh at IPC

A voltage source converter controlled with PWM generates voltage harmonics at frequencies close to multiples of the switching frequency. State of the art converters work with a frequency between 3 and 20 kHz and produce harmonic oscillations in the range of 3 to 80 kHz. Low grid impedance at these frequencies will result in relatively high currents circulating between the intermediate circuit of the inverter and any electronic equipment connected to the IPC. Capacitors of the CLC line filter of that equipment will absorb the harmonics current. Resulting thermal losses in the capacitor will shorten its lifetime. Knowing at which frequencies the grid impedance is the lowest, it is possible to undertake actions in order to avoid generation of harmonics at frequencies close to those frequencies or to restrain their transmission.

State of the Art in grid impedance measurement

Spectral grid impedance is the ratio between the amplitude of a harmonic oscillation in Volts and the resulting oscillating current flowing to the grid at the same frequency.

$$\underline{Z_h} = \underline{U_h} / \underline{I_h}$$

Efficient spectral grid impedance measurement needs to be:

- able to measure “on-line”, with working loads an sources
- non-intrusive,
- stable over the full frequency spectrum,
- fast and accurate.

On-line measurement methods for non-fundamental frequency impedance are well reviewed in [5]. The basic concept of the measurement is represented in figure 4, with injection of a harmonic current and measurement of the resulting harmonic voltage component. The spectral impedance can be gained by calculating the ratio between harmonic voltage and harmonic current at defined frequencies over the measuring range.

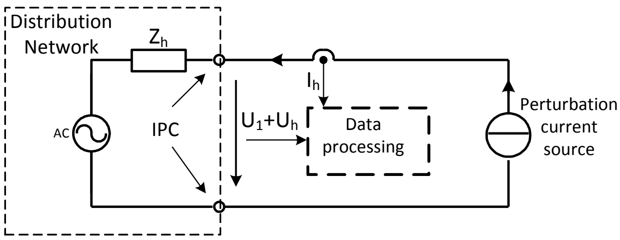

Fig.4.: Principle of grid impedance measurement

Two methods are described in the literature on the subject:

- Injection of a perturbation current generated by a transient phenomenon, such as the switching of a resistor or a capacitor serial or parallel to the power supply system. This method has the advantage of speed, as a wide range of frequencies is generated at the time. Data processing will usually require Fast Fourier Analysis (FFT). [3] [4].
- Injection of a single frequency sinusoidal current component by precision controlled current source. The data is processed at each tested frequency and the whole frequency domain scanning will take longer. This method is accurate and an exact selection of tested harmonics frequencies is possible. [2] [5] FFT can however be supplemented by more efficient data processing methods.

IMPLEMENTATION

At the start of our project we had the opportunity to use the MZF Grid Impedance Meter with a frequency range of 2.5kHz designed by Montena EMC. This device has been a great source of inspiration for us. The following choices helped us realize a fast and accurate meter with a wider frequency range:

Single frequency sinusoidal current injection: In comparison with the transient phenomenon method, single frequency injection makes it possible to determine with accuracy the amplitude of the signal injected at any frequency. This way, we can guarantee that the whole spectrum is covered with the desired perturbation power. Problems related to frequency domains reserved for communication can be avoided if needed and the test will be less intrusive than a test generating wide spectrum perturbation.

Direct coupling: Devices based on a single frequency sinusoidal current injection usually include a decoupling circuit between the amplifier and the power supply line [2] [5]. The aim of the decoupling is to reject the fundamental frequency, so that the amplifier and measuring devices can be sized for very low voltage only. The drawback of this method is the difficulty to keep the source impedance constant over a wide frequency range due to the parasitic components of the decoupling filter. We decided to do without decoupling and to connect our current source directly to the low voltage distribution grid.

Class A/B amplifier topology: An accurate and distortion free current source can be relatively easily achieved with a class A/B amplifier topology. In case of direct coupling, this circuit requires a bipolar DC supply with a voltage higher than the maximal amplitude of the LV grid voltage. The class A/B topology generates power losses proportional to the supply voltage and to the output AC current. The first version of the amplifier provided an AC output current of 50mArms, resulting in reasonable losses in the amplifier and power consumption from the battery. However, grid impedance measurements with such a low current did not show satisfying results, mainly because of harmonics present on the grid in the low frequency range. The output current was increased up to 200mArms. This relatively high perturbation current corresponds generally to the maximum acceptable value for electronic loads connected to the grid.

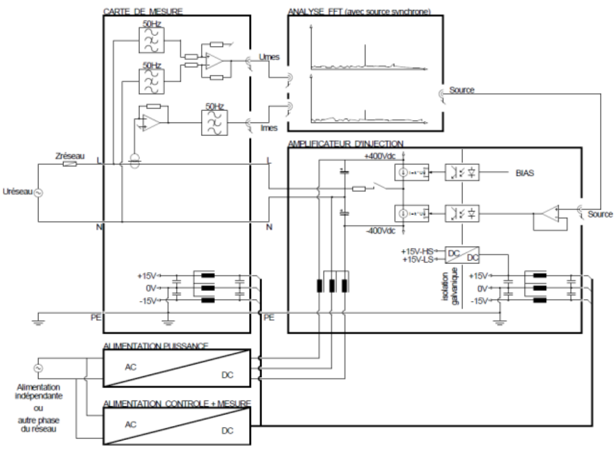

Fig. 5.: Block diagram of the IGOR-Meter III

Battery supply: Unless very carefully designed, any power supply connected to the grid will generate some perturbations or influence its spectral impedance. In order to keep measuring accuracy high, the Impedance Meter is supplied with an external battery. Creating a DC voltage over ±370V from battery voltage level is not easy. A special supply module available on the market is used for this purpose.

DATA PROCESSING AND SINUS GENERATOR

The time requirements of the single frequency current injection method can be counterbalanced with faster and more efficient data processing than Direct Fourier Transform (DFT): Synchronous or Coherent Demodulation (DMS) has been widely used in high performance AM radio receivers or lock-in amplifiers. The following DMS digital data processing was implemented in an FPGA: the sinusoidal control signal of the perturbation current amplifier:

$$V_{test} = V_{ref} \cdot \sin(\omega_r \cdot t + \varphi_{ref})$$

is multiplied after A/D conversion with the measured current and voltage signals

$$V_{meas} = V_{sig} \cdot \sin(\omega_m \cdot t + \varphi_{sig})$$

The product includes two oscillations, one at the frequency difference (ω_m–ω_r), the other at the frequency sum (ω_m+ω_r):

$$\begin{aligned} V_{psd} &= V_{sig} \cdot V_{ref} \cdot \sin(\omega_m \cdot t + \varphi_{sig}) \cdot \sin(\omega_r \cdot t + \varphi_{ref}) \\ &= \tfrac{1}{2} \cdot V_{sig} \cdot V_{ref} \cdot \cos((\omega_m - \omega_r) \cdot t + \varphi_{sig} - \varphi_{ref}) - \\ &\quad \tfrac{1}{2} \cdot V_{sig} \cdot V_{ref} \cdot \cos((\omega_m + \omega_{ref}) \cdot t + \varphi_{sig} + \varphi_{ref}) \end{aligned}$$

At the test frequency, we have $\omega_m = \omega_r$. The DC component

$$V_d = \tfrac{1}{2} V_{sig} \cdot V_{ref} \cdot \cos(\varphi_{sig} - \varphi_{ref})$$

of the product result is proportional to the In-Phase component of the voltage or current at the tested harmonic frequency. In-phase component or real part of $\underline{U_h}$ or $\underline{I_h}$ can be gained by low pass filtering of the product signal V_{psd}.

A similar process with a 90 degree phased shifted oscillation will result in V_q, the quadrature component or imaginary part of $\underline{U_h}$ or $\underline{I_h}$. Amplitude and phase of $\underline{U_h}$ or $\underline{I_h}$ can be gained by computing the magnitude and phase of the signal vectors V_d and V_q:

$$|U_h| \text{or} |I_h| = \sqrt{{V_d}^2 + {V_q}^2} = \frac{1}{2} \cdot V_{sig} \cdot V_{ref}$$

$$\varphi(U_h) \text{or } \varphi(I_h) = \arctan\left(\frac{V_q}{V_d}\right) = \arctan\left(\frac{\sin(\varphi_{sig} - \varphi_{ref})}{\cos(\varphi_{sig} - \varphi_{ref})}\right)$$

A detailed description of the process can be found in [7].

A block diagram of the complete signal processing is represented in figure 6, including Sine and Cosine generators, synchronous demodulation filtering as well as magnitude and phase computation of $\underline{Z_h}$.

Bipolar DC/DC power supply, current source amplifier, voltage and current sensors, analogue notch filters board and FPGA are mounted on a compact 19'' rack. The unit is completed with an embedded ARM processor board, a so called uGate, which will control the process and interface the Impedance Meter with the control PC which handles the storage of data results and graphical display.

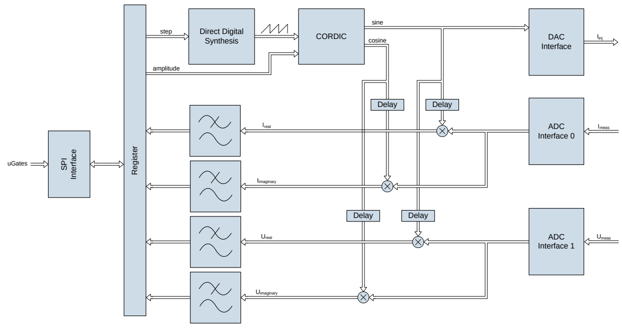

Fig. 6.: Block diagram of the data processing unit

TEST RESULTS

On-line impedance measurement of an EMC filter with known components corresponded to the calculated impedance. Those results were also compared with off-line measurements of the filter using an SR1 audio analyzer. Full frequency range measurement with 1000 harmonic frequency steps takes less than 1 min. In the frequency range over 1.5 kHz, results with a perturbation current of 140mArms are very satisfying in both phase and magnitude. Measurements at a frequency below 1.5 kHz need particular attention, as the presence of high amplitude harmonics will create noise on both magnitude and phase plots. Repeated runs with averaging can improve tests accuracy. Results of On-Line Spectral Impedance measurements of the low voltage distribution supply in our laboratory with two different inverters are shown in figure 7.

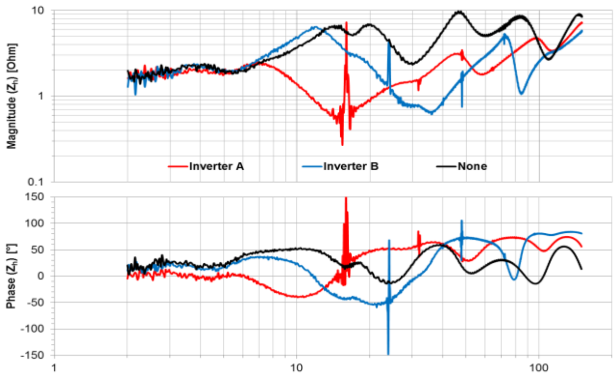

Fig. 7.: Spectral impedance of laboratory supply line

The impedance meter helped us analyze the interaction between two different PV inverters connected to a IPC with short lines. Before connection, measurements with FFT showed that inverter A generated harmonics at 16 and 32 kHz. On-line impedance measurements with inverter B line showed that the EMC filter had a serial resonance with impedance below 0.7Ohm at 32kHz. We could foresee that after the connection of both inverters, the harmonic currents around 32 kHz generated by semiconductor switching of inverter A would increase significantly due to the low global impedance at this frequency. FFT analysis of the current measured at the output of inverter A with and without the presence of inverter B confirmed our prediction: after the connection, harmonic current around 32kHz increased by a factor of 3.

One easy, but costly solution to reduce the circulating harmonic current down to acceptable values would be to reinforce the harmonic filtering with larger inductors or capacitors or to install a new filter. A more cost effective solution based on the spectral supply impedance analysis would be to shift the resonance of the EMC filter toward a slightly higher frequency. This could be achieved with the use of smaller instead of larger components. A small change in the switching frequency of inverter A could also be considered as another alternative.

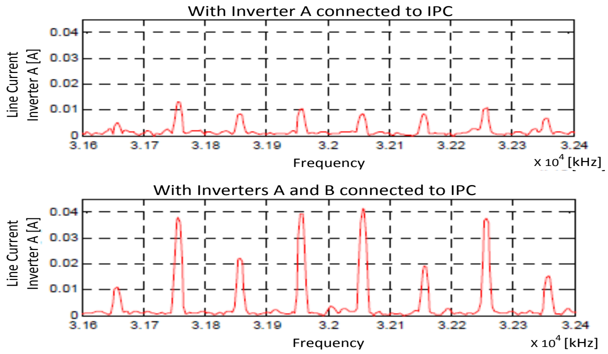

Fig. 8.: Harmonic currents circulating between PV inverters

CONCLUSION

Accurate and fast on-line measurement of the impedance in frequency up to 150kHz can be achieved on site with the method and apparatus we developed within the IGOR project (Interferences Generated by inverters On the Grid). Evaluation of the spectral impedance of the grid over a wide spectrum can be used to analyze problems of interactions between multiple sources, typically present in case of high penetration of distributed energy resources.

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