Time domain methods for the analysis of conducted interference on the power supply network of complex installations

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Abstract—Conducted spurious phenomena cause interference in the power supply network of complex installations. The time dependent behaviour of these phenomena calls for dedicated measurement techniques in time domain. Quantities to measure are defined for DM as well as CM. Various measurement sensors are designed, implemented, characterised and tested. Frequency domain measurement equipment is not suitable for these time variant disturbances. Signal processing on the time domain data provides the necessary characteristics of the system. The proposed measurement methods provide a basis for the analysis of conducted behaviour of equipment as well as fixed installations.

Index Terms—power drive system; time variant periodic asynchronous; EFT; 150 kHz; LV-network; time-domain measurements;

I. INTRODUCTION

The development of fast switching high power transistors made it possible to implement sophisticated power electronics in a variety of widely used applications, such as switched mode power supplies (SMPS), power drive systems (PDS), active in-feed converters (AIC) for PV installations and energy efficient compact lamps. Also modern washing machines, ventilation systems, air-conditioning units, water pumps and other mechanical applications use a kind of PDS. These equipment cause a lot of noise on the power leads, mainly in the frequency range from a few kHz to 150 kHz, but often even much higher. For PDS there is a product standard [1] that warns for possible radio interference in which case supplementary mitigation measures may be required. At the same time, there is an increased use of signalling on the low voltage (LV) grid, e.g. for power line communication (PLC) for smart metering. It should not be a surprise that interference problems are observed.

Until recent, emission limits in civil EMC standards ([2] and [3]) have been focused on the protection of radio broadcast and mobile communication services. Discussions on radiated and conducted emission requirements started with the beginning of long wave radio broadcasts in the 1920’s [4]. Therefore it is no coincidence that these standards start at 150 kHz. For the purpose of Power Quality (PQ) there are requirements on harmonics and inter-harmonics up to 2 or 2.4 kHz. Military standards, like the AECTP-501 [5] do require conducted emission tests on the power leads from 30 Hz to 10 MHz in order to reduce EMI towards the power distribution system, to prevent hull currents on naval ships, and to protect military radio services that operate well below the civil 150 kHz boundary. This is one of the gaps between civil and military standards that puts a challenge on the integration of commercial off the shelf (COTS) equipment in modern naval shipbuilding [6]. So there is an uncovered frequency range of 2 to 150 kHz in civil EMC standards (with the exception of CISPR 15 [7]) that only recently gets attention for EMC as mentioned before in [8]. Therefore, there is an interest for test and measurement of time-variant, asynchronous, periodic transient phenomena on the LV-grid as well as the propagation of this noise. EMI interactions need to be identified as well as its probability of occurrence. This research has begun already. For example, two new test and measurement standards are proposed [9], [10]. In [11], a number of standardised measurement methods are proposed.

Section II shows examples of interference from spurious phenomena and the time dependent behaviour that calls for dedicated measurement techniques, for which the parameters to be measured are in section III. The sensors to measure these parameters are developed in Section IV. An implementation of these sensors is characterised in Section V and tested in Section VI.

II. SPURIOUS PHENOMENA ON LV NETWORKS AND THEIR DISTURBING EFFECTS

Disturbing effects vary from flickering lights due to incorrect operation of dimmers, incorrect readings from smart meters, not reachable smart meters and ultrasonic medical equipment [12]. We also have seen malfunctioning of PV inverters due to emissions in the frequency range from 2 to 150 kHz coming from a PDS for a ventilation system [13].
Time signal systems like DCF77 also operate in the uncovered frequency range. LF RFID at 134.2 kHz has been in use for a few decades. Integrated circuits for this application and frequency are readily available at low cost. The communication protocol is standardised, but the frequency use is not regulated, as the powers are low and it does not interfere with commercial radio broadcast or mobile communication services. This technology is not designed with the presence of the periodic and transient noise from the equipment with fast switching high power transistors in mind.

In [14] it is shown that electric fast transients (EFT) from the LV network are capable of disturbing or disrupting Ethernet communication at protocol level. The protocol seems not to be designed to handle EFT phenomena in an efficient way, even when high quality cables are used with low expected crosstalk [15].

While harmonic currents are mostly redirected by the feeding cables and dissipated in the supplying LV transformer, higher frequency currents over long lines will radiate and produce electromagnetic fields. As stated before, settled emission limits should prevent radio disturbances for frequencies above 150 kHz.

Measurements have been performed to investigate the impact of the spurious signals that state of the art equipment in an industrial environment produce on the LV network and the results are shown in Fig. 1. Its spectrum is displayed in Fig. 2. This spectrogram is obtained by applying a stepped time Fourier transform (STFT) on the data. The bulk current in Fig. 3 with its spectrum in Fig. 4 is measured in the same industrial environment. Bulk current measurements showed the same characteristics in the entire environment. These measurements are performed with a conventional current clamp with a cut-off frequency of about 150 kHz. Fig. 5 shows the bulk current, measured on a special earth rod near a water pump behind a VFD. Its spectrum is in Fig. 6.

The observed time-dependent periodic signals might appear as random signals but are often in fact synchronous with the waveform of the supplying power [16]. This time domain behaviour makes time domain measurement equipment most suitable for the analysis of these kind of spurious phenomena. However, frequency domain measurement equipment such as spectrum analysers and EMI measurement receivers seem attractive for their high sensitivity, selectivity and dynamic range.
as well as their ease of use. They are not suitable for these time dependant signals except if special features such as time gating are applied. Time domain EMI receivers on the market nowadays can be used, but they are expensive. Time domain equipment such as a digital sampling oscilloscope is generally limited to 8 bits samples, which can provide a dynamic range of 48 dB if the scale is carefully chosen. To make time-domain measurements of high frequency phenomena within at least one cycle of the power supply it is necessary to store a high number of samples. For example, to analyse frequencies up to 1 MHz during a measurement window of 50 ms (2.5 cycles), 100 000 samples need to be stored. This data set can be used to obtain a lot of characteristic information from the time domain measurements. A standard discrete Fourier transform (DFT) of the data will result in a resolution of 20 Hz.

The frequency of interest for this research is not limited to 2 to 150 kHz, but will extend from DC to several MHz, because this is the operation range of a lot of disturbing equipment in industrial areas. For these low frequencies, short leads will not radiate and so does not measurement equipment when measuring voltages and currents locally.

III. DEFINITIONS OF VOLTAGES AND CURRENTS

Fig. 7 and 8 define the voltages and currents on the live (L), neutral (N) and protective earth (PE) in a one phase LV network. For a three phase system, similar definitions apply. Although all currents flow in complete loops, the defined voltages and currents can be defined locally as long as the wavelength is much longer than the sensors and measurement equipment, including the leads.

- Non-symmetric mode: \( V_L, V_N, I_L, I_N, I_{PE} \). All voltages are local, so the PE can be taken as reference, which makes measurements easy.
- Symmetric (differential) mode:
  \[
  V_{dm} = V_L - V_N \quad (1) \\
  I_{dm} = I_L - I_N \quad (2)
  \]
- A-symmetric (common) mode:
  \[
  V_{cm} = \frac{V_L + V_N}{2} \quad (3) \\
  I_{cm} = \frac{I_L + I_N}{2} \quad (4)
  \]
- Bulk current (common mode for L, N and PE):
  \[
  I_{bulk} = I_L + I_N + I_{PE} \quad (5)
  \]

Note that there is no such thing as bulk voltage. For the a-symmetric current, the return current flows via the PE, while for the bulk current, the return current flows in a different path, outside the reach of these sensors.
IV. MEASUREMENT SENSORS

To measure the voltages and currents that are defined in Section III, several sensors have been developed. The goal is to have sensors that have a flat characteristic with minimal phase distortions to perform extensive in-situ measurements for the analysis of the spurious phenomena and their disturbing effects as mentioned in Section II.

The sensor for the non-symmetric voltage, Fig. 9, has been developed by two simple voltage dividers for both L and N, relative to PE. This sensor also measures the supply voltage at the mains frequency itself, which limits the dynamic range for the lower voltages at higher frequencies.

The sensor for the CM voltage, Fig. 10, includes a third order filter to eliminate the supply voltage at the mains frequency, allowing the full dynamic range of the equipment for the higher frequency phenomena.

The sensors for the CM and DM currents, Fig. 11 and 12 respectively, are made by winding electricity wire around a toroid core made from N30 ferrite material. The numbers under the coil assemblies are turns ratios.

The bulk current sensor, Fig. 13, is in fact a conventional current clamp. The three current sensors from Fig. 10, 12 and 13 are calibrated with a jig, comparable to the method in CISPR 16-1-2 [17].

V. CHARACTERISATION OF MEASUREMENT SENSORS

The sensors that are described in Section IV are characterised by an oscilloscope with signal generator. A sine wave is frequency swept and applied to the input ports. The sine wave, the output ports and measurement ports are measured at the oscilloscope in amplitude and phase, of which the latter is not shown in this paper. Characterisation is done for connection in a-symmetric mode, i.e. L and N shorted, relative to PE, and in symmetric mode, i.e. between L and N, with floating PE.

Fig. 14 and Fig. 15 show the transfer function of the sensors, which illustrate that the CM and DM current sensor behave as a choke for their pertaining mode at their working frequencies.
The measured voltage transfer of the voltage sensors are shown in Fig. 16. It can be seen that the dynamic range of the non-symmetric voltage sensor is lacking in this measurement. Finally, the transfer impedance of the current sensors is in Fig. 17.

One observation from these characterisation measurements is the fact that inductors and metal parts of the measurement set-up interact capacitively with its surroundings from about 1 to 10 MHz. This shows that the accuracy of measurements above this threshold is affected negatively and capacitive coupling must be taken into account. For in-situ equipment testing, the CM and DM impedances of the mains network can be simulated by an Artificial Mains Network (AMN). To analyse the propagation of interferences on this network as well as to investigate mitigation techniques, the real network has to be used, but also characterised. Measurement and analysis methods for this mains impedance is proposed by others [13], [18].

VI. EXPERIMENTAL VALIDATION

The defined voltages and currents are measured for equipment that is connected to the power grid via an AMN according to CISPR16-2-1 [19], to eliminate other disturbances that are present on the mains supply. One example equipment is shown in this paper. It is a modern SMPS feeding a laptop. Fig. 18 shows the resulting CM voltage and current as well as the bulk current. The latter is small in this case, since the equipment is isolated and only the SMPS is earthed via the PE connection. For the analysed frequencies, the capacitive coupling of the equipment under test (EUT) to its surroundings can be neglected. The respective spectrograms of these measurements, Fig. 19, 20 and 21 show that most signals are well below the 150 kHz boundary. These results show spurious phenomena that are periodic, have a time-variant amplitude as well as frequency, but are not coherent with the mains frequency.

![Fig. 16: Measured voltage transfer of voltage sensors.](image1)

![Fig. 17: Transfer impedance of current sensors.](image2)

![Fig. 18: Measured voltage and current towards a modern SMPS of a pc.](image3)

![Fig. 19: Spectrogram of $I_{cm}$ towards a modern SMPS of a pc.](image4)
Conducted spurious phenomena cause interference in the power supply network of complex installations. Most of these conducted signals are in the frequency range of 2 to 150 kHz, that is not covered by civil EMC standards. The time dependent behaviour of these phenomena calls for dedicated measurement techniques in time domain. Quantities to measure are defined for DM as well as CM. Various measurement sensors are designed, implemented, characterised and tested. Frequency domain measurement equipment is not suitable for these time variant disturbances. The proposed measurements are all defined locally. The behaviour of the power supply network could be simulated by an AMN, but to analyse the propagation of interferences on this network as well as to investigate mitigation techniques, the real network must be used, but also characterised. Signal processing on the time domain data provides the necessary characteristics of the system. The proposed measurement methods provide a basis for the analysis of conducted behaviour of equipment as well as fixed installations.

VII. CONCLUSIONS

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