Efficient immunity testing of smart meter devices in the frequency range 2-150 kHz

Frank Gronwald
Hamburg University of Technology
Germany
gronwald@tuhh.de

Ralf Conrads and Reinhard Janssen
EWE AG Oldenburg
Germany
ralf.conrads@ewe.de; reinhard.janssen@ewe.de

Thomas Weber
TÜV NORD CERT GmbH
Germany
tweber@tuev-nord.de

ABSTRACT

Energy networks are subject to considerable disturbing currents in the frequency range of 2-150 kHz, due to insufficient Electromagnetic Compatibility standards, and it is important that smart meter devices exhibit in this frequency range sufficient immunity. It is shown that corresponding immunity tests in frequency domain must utilize small enough frequency spacing since smart meter susceptibilities can be rather narrowband, as is shown by example. It is also pointed out that for efficient testing the use of broadband test pulses provides advantages if compared to single frequency sweeps.

INTRODUCTION

It is known that smart meter devices can be subject to conducted disturbances that seriously affect operational states. The related EMC-problems are of particular concern in the frequency range 2-150 kHz [1]. This frequency range, at present, is not satisfactorily regulated by obligatory EMC standards, as can be seen from the EMC standards that *are* currently in effect and concern immunity testing of smart meter devices. These comprise the following basic standards, as listed in the relevant product standard IEC 62052-11 [2]:

- Standard IEC 61000-4-2 which is related to immunity testing with respect to electrostatic discharge [3].
- Standard IEC 61000-4-3 which is related to immunity testing with respect to external radiated electromagnetic fields in the frequency range 80 MHz to 2 GHz [4].
- Standard IEC 61000-4-4 which is related to immunity testing with respect to fast transients and bursts, as can be produced by fast switching processes [5].
- Standard IEC 61000-4-5 which is related to immunity testing with respect to transients of a double exponential form, as can be produced by lightning or slow switching processes [6].
- Standard IEC 61000-4-6 which is related to immunity testing with respect to conducted disturbances in the frequency range 150 kHz to 80 MHz [7].
- Standard IEC 61000-4-12 which is related to immunity testing with respect to non-repetitive damped sinusoidal transients that also are called "ring waves". The test frequencies of these sinusoidal transients are given by 100 kHz and 1 MHz [8].

Concerning immunity testing with respect to conducted disturbances, it is seen that the relevant basic standard IEC 61000-4-6 only covers the frequency range 150 kHz to 80 MHz. A closer inspection of this standard additionally reveals that only common mode signals are applied to the test objects, while in typical energy distribution networks it is the differential mode which is mostly relevant [9,10].
To also take into account conducted differential mode disturbances in the frequency range below 150 kHz, a new basic standard IEC 61000-4-19 with draft title "*Testing and measurement techniques - Test for immunity to conducted, differential mode disturbances in the frequency range from 2 kHz to 150 kHz, at a.c. ports*" is currently under discussion. It is not yet known when this standard will be finalized and whether it will be made obligatory for smart meter devices. Also, it still needs to turn out in practice whether the test procedures described in this standard will be sufficient enough to assure proper functioning of smart meter devices under all circumstances that are usually encountered in power distribution networks.
To summarize, it can be stated that at present there is no international and standardized test procedure in effect which guarantees a proper immunity of smart meter devices with respect to conducted disturbances in the frequency range 2-150 kHz. Clearly, this situation is not satisfying for the manufacturers and users of smart meter devices since it is left to their own responsibility, at least to a considerable extent, to assure sufficient EMC immunity of their smart meter devices within actual energy networks.
While the draft standard IEC 61000-4-19 already provides guidance with respect to comprehensive immunity testing in frequency domain, the following points are noted:

- Due to the finite frequency spacing of the narrowband test pulses it is possible that narrowband susceptibilities of smart meter devices are missed.
- Testing in the frequency domain is considered as time-consuming since, depending on the frequency spacing, hundreds of test frequencies have to be considered to cover the whole frequency range 2-150 kHz. This issue becomes a serious problem if a smart meter devices is tested which for the test engineer requires many seconds to evaluate the operational state of the device under test.

In this contribution we reconsider the physical basis of immunity testing in frequency domain. It will be seen that the susceptibility of smart meter devices can be considerably narrowband such that broadband test pulses that are defined in time should also be considered to obtain more reliable test results.

IMMUNITY TESTING AND QUALITY FACTORS OF COMPLEX SYSTEMS

From the point of view of EMC modelling, a smart meter device is not a canonical structure, such as a simple transmission line or antenna, but rather a complex system. Usually, linearity and time-invariance is assumed and then the immunity of a complex system often is characterized by a transfer function $H(s)$ which relates an output quantity, such as the observable $O(s)$ of an operational state, to an input quantity, such as a disturbing current $I(s)$. These transfer functions can be discussed in the framework of the so-called singularity expansion method (SEM) and then are written in the general form

$$H(s) = \frac{O(s)}{I(s)} \approx \sum_{m=1}^{M} \left(\frac{R_m}{s - s_m} + \frac{R_m^*}{s - s_m^*} \right) \tag{1}$$

where the approximation sign indicates that in general the relation is not a mathematically exact equality but of sufficient accuracy if M dominant poles s_m of the system are taken into account. These poles represent the frequencies where the complex system considered is potentially susceptible to the input quantity $I(s)$. The variable s denotes the Laplace variable in the complex plane and for the m^{th} pole the variable R_m denotes the residue associated to each resonance pole,

$$s_m = \sigma_m + j\omega_m \tag{2}$$

The real part σ_m, for passive systems, is negative and represents losses of the system, the imaginary part ω_m is the resonance frequency associated to the pole s_m. If the representation (1) is compared to the transfer function of a damped harmonic oscillator, such as an *RLC* resonant circuit, it is seen after some analysis that the variables σ_m and ω_m can also be expressed in terms of an Eigenfrequency $\omega_{0,m}$ and a quality factor Q_m. The corresponding relations are given by [5]

$$\omega_{0,m} = |s_m| \qquad Q_m = -\frac{\omega_{0,m}}{2\sigma_m} \tag{3}$$

These notions and concepts are important in order to correctly interpret immunity testing in frequency domain [13]. As an example, in Fig. 1 the frequency dependency of the received power of a small dipole antenna is displayed in the vicinity of resonance, serving as an elementary model of an EMC victim. At resonance, the received power attains a maximum and the susceptibility of this system becomes, in this frequency range, largest as well. For reliable immunity testing it is decisive to hit the maxima of susceptibility and this, in turn, requires choosing the frequency steps accordingly. If testing with a margin of 1dB with respect to maximum susceptibility is desired this requires, in the example of Fig. 1, to choose frequency steps f_n according to a 2.3% rule, that is,

$$f_{n+1} = f_n \cdot 1{,}023 \tag{4}$$

as can be seen from Fig. 1 where the 2,3% bandwidth is indicated. This measure is closely connected to the quality factor Q = 23 of the system, the reciprocal of which indicates the 3dB-bandwidth.

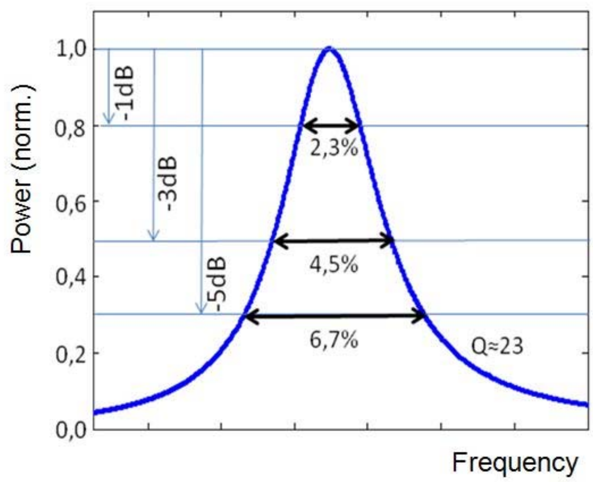

Figure 1. The diagram shows the received power of a matched, small dipole antenna of quality factor Q = 23. It can be noted that the quality factor is given by the reciprocal of the percentage of the 3db-bandwidth relative to the resonance frequency, i.e., Q = 23 ~ 1/(0.045).

In the draft standard IEC 61000-4-19, frequency steps are prescribed according to a 2% rule. This allows reliable testing of systems up to a quality factor of 26 if a 1 dB margin is desired. For higher quality factors it is then possible to miss frequencies where susceptibility is at a maximum and, as a consequence, immunity at a minimum. For smart meter devices it is not immediate to determine a quality factor on the basis of physical models. The reason is that smart metering involves a considerable amount of digital signal processing which is not directly accessible to electromagnetic theory. That is, within a smart metering device analog signals are readily converted to digital signals

and then further processed. Disturbances in the frequency range 2-150 kHz may affect this process but there is no general rule for this since it strongly depends on the actual AD converter.
In order to obtain more information on typical quality factors of smart meter devices, if considered as an EMC victim, an actual smart meter has been investigated by means of an EMC test setup which is sketched in Fig. 2. A rather small frequency step width of 0.37% was chosen, yielding the result curve of Fig.3.

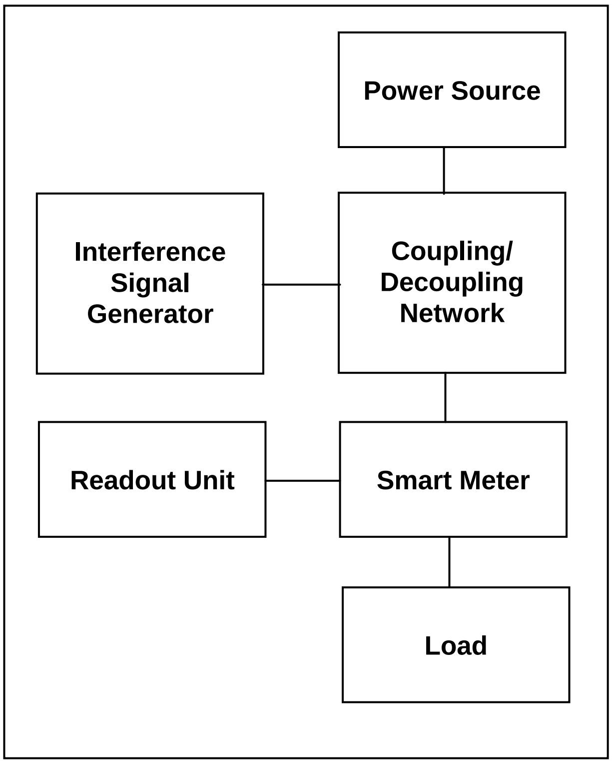

Figure 2. EMC test setup which is suitable to investigate the immunity of smart meter devices. It follows the generic setup for conducted immunity tests [10]. Special care must be taken, however, that the coupling/decoupling network is adapted to the required frequency range 2-150 kHz.

The test result exhibits narrowband susceptibilities that lead to abnormal operational states where acceptable accuracy limits are clearly exceeded. To exhibit these narrowband susceptibilities, a frequency step width of 0.37% proved to be useful.
The visible peaks can be approximated by resonance peaks of the mathematical form displayed in Fig. 1, even though this analogy is physically somewhat vague since it can be assumed that the observed narrowband failure of the smart meter device is due to poor filtering or poor signal processing of high-frequency disturbances rather than due to a physical resonance. Then the associated quality factors of the observed peaks clearly exceed the value of 26 which is identified as the maximum value that can be analyzed by means of a standard frequency step width of 2%. Therefore it turns out by this example that the susceptibility of actual smart meter devices can be narrowband to an extent which makes it necessary to use a much finer frequency stepping than the standard one.

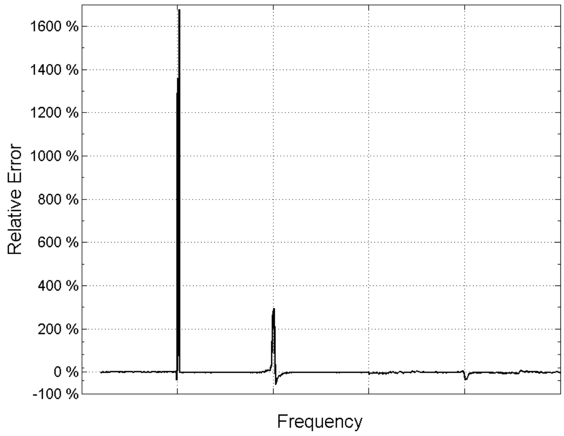

Figure 3. Result of immunity testing of an actual smart meter device. Two pronounced susceptibilities which indicate an abnormal operational state can clearly be recognized.

NARROWBAND VERSUS BROADBAND TEST SIGNALS

As already mentioned in the introduction, the use of small frequency steps is not always practical since it can be connected to a considerable increase of test time. Therefore it is recommended to also use broadband test signals which reduce the risk of missing susceptibilities due to insufficiently large frequency steps. In the context of the EMC of complex systems this idea is not new and leads to the question whether certain test pulses are equivalent but more time efficient if compared to single frequency continuous wave signals. Discussions of this point can be found, in particular, in the context of "Intentional Electromagnetic Interference (IEMI)". In relation to energy networks a corresponding investigation with useful literature is given in [14].
Here we limit ourselves to mention the double exponential pulse

$$I_{\exp}(t) = I_{0,\exp}\left(\exp(-\alpha t) - \exp(-\beta t)\right) \tag{5}$$

and the damped sinusoidal pulse

$$I_{\sin}(t) = I_{0,\sin}\exp(-\delta t)\sin(\omega_0 t) \tag{6}$$

It is interesting to note that these waveforms, with certain specified parameters, already are utilized in the standards

IEC 61000-4-4 [5] and IEC 61000-4-12 [8] which are prescribed for smart meter devices. However, they are not yet used to close the standardization gap in the frequency range 2-150 kHz.
The waveforms (5) and (6) have the advantage that their Fourier transforms can easily be obtained as

$$\tilde{I}_{\exp}(\omega) = I_{0,\exp} \frac{(\beta-\alpha)}{(\alpha - j\omega)(\beta - j\omega)} \tag{7}$$

and

$$\tilde{I}_{\sin}(\omega) = I_{0,\sin} \frac{\omega_0}{\omega_0^2 + \left(\delta^2 + j\omega^2\right)} \tag{8}$$

These analytic formulas allow estimating the energy E_I of a pulse by means of Parseval's theorem

$$\int_{-\infty}^{\infty} I^2(t)dt = \frac{1}{2\pi}\int_{-\infty}^{\infty} \left|\tilde{I}(\omega)\right|^2 d\omega \equiv E_I \tag{9}$$

which also yields an estimate of the energy $E_{I[\omega_1,\omega_2]}$ in a certain frequency interval $[\omega_1, \omega_2]$, given by

$$\frac{1}{2\pi}\int_{\omega_1}^{\omega_2} \left|\tilde{I}(\omega)\right|^2 d\omega \equiv E_{I[\omega_1,\omega_2]} \tag{10}$$

For different test pulses to be equivalent, the corresponding energies must be comparable in the considered frequency interval.
Modern signal generators that can be taken as interference signal generator in a test setup as shown in Fig. 2, usually provide a host of predefined test signals, including the double exponential pulse and the damped sinusoidal pulse, which can repetitively be applied. It has not explicitly been shown by the authors, yet, which test signal is an optimal choice in terms of efficiency and reliability. However, the susceptibilities observed in Fig.3 actually were first discovered by experimenting with different pulse shapes rather than by applying frequency sweeps. Therefore the use of broadband pulses is suggested as a promising means for efficient and reliable testing of smart meter devices.

REFERENCES

[1] CENELEC SC 205A, 2010, *Study Report on Electromagnetic Interference between Electrical Equipment/Systems in the Frequency Range below 150 kHz*, SC205A/SEC0260/R.

[2] IEC 62052-11, 2003, *Electricity metering equipment (AC) - General requirements, tests and test conditions - Part 11: Metering equipment.*

[3] IEC 61000-4-2, 2008, *Electromagnetic compatibility (EMC) - Part 4-2: Testing and measurement techniques - Electrostatic discharge immunity test.*

[4] IEC 61000-4-3, 2010, *Electromagnetic compatibility (EMC) - Part 4-3: Testing and measurement techniques - Radiated, radio-frequency, electromagnetic field immunity test.*

[5] IEC 61000-4-4, 2012, *Electromagnetic compatibility (EMC) – Part 4-4: Testing and measurement techniques – Electrical fast transient/burst immunity test*.

[6] IEC 61000-4-5, 2005, *Electromagnetic compatibility (EMC) - Part 4-5: Testing and measurement techniques - Surge immunity test.*

[7] IEC 61000-4-6, 2008, *Electromagnetic compatibility (EMC) - Part 4-6: Testing and measurement techniques - Immunity to conducted disturbances, induced by radio-frequency fields.*

[8] IEC 61000-4-12, 2006, *Electromagnetic compatibility (EMC) - Part 4-12: Testing and measurement techniques - Ring wave immunity test.*

[9] R. Strzelecki and G. Benysek (eds.), 2008, *Power Electronics in Smart Electrical Energy Networks* (Springer, London, United Kingdom).

[10] C.R. Paul, 2006, *Introduction to Electromagnetic Compatibility*, 2nd ed., (Wiley, New Jersey, USA).

[11] C.E. Baum, 1976, "The Singularity Expansion Method", in *Transient Electromagnetic Fields*, L.B. Felsen (ed.), (Springer, Heidelberg), 129-179.

[12] J. Chauveau, N. de Beaucoudrey, and J. Saillard, 2007, "Characterization of Perfectly Conducting Targets in Resonance Domain with their Quality of Resonance", *Progress in Electromagnetic Research,* vol. 46, 165-188.

[13] F. Gronwald, T. Stadler, R. Kebel, 2012, "Compensation of Unavailable Test Frequencies during Immunity Measurements", in *Proceedings of ESA Workshop on Aerospace EMC,* (ESA, SP-702).

[14] W. Radasky and E. Savage, 2010, "Intentional Electromagnetic Interference (IEMI) and Its Impact on the U.S. Power Grid", (Metatech, Meta-R-32).