A POSSIBILITY TO MEASURE POWER QUALITY WITH RC-DIVIDER

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ABSTRACT

Power quality in modern networks is becoming more and more important. The results of first measurements made with conventional instrument transformers in MV, HV and EHV networks show that frequency response is dependent on system voltage. Based on these results and the necessity of correct measurement results up to a higher frequency range, other more precise measuring systems have to be looked at. Only such equipment will be able to guarantee the correct measurement of power quality parameters up to the EHV-level.

In this paper, the measurement of harmonic frequencies with a very high accuracy over a wide frequency range using a non-conventional instrument transformer is illustrated. This technology can be used for MV, HV and also up to EHV system networks.

The paper begins with a short introduction. In the next chapter the theoretical aspects are illustrated, followed by a detailed description of the RC-divider technology. Then the physical limitations and requirements of this technology are discussed. In the following chapter international standards and the definition and calculation of accuracy are explained. Measurement results from 15Hz up to 10kHz will be illustrated and compared with measurements of conventional inductive instrument transformers.

INTRODUCTION

Within the last decade, existing power networks are in the process of changing very dynamically. The production of electrical energy using alternative sources of energy is becoming more and more important. The power quality is highly affected by, for example, HVDC links, wind parks and non-linear electrical loads. As a result, high-frequency voltage affects the high-voltage insulation of the installed equipment. Due to the skin effect, thermal overload on conductors may occur. Therefore, it is important to know the level of harmonic voltages and currents in the system. Appropriate measuring instruments with a high accuracy up to higher harmonics of the fundamental frequency are needed. Network operators have to have this data in order to be able to start analysis and be able to initiate appropriate countermeasures. IEC61000-4-30 defines the measuring methods, measuring ranges and the accuracy of the measurement system. The instrument transformers are considered in standard IEC61869-1 “General requirements” and in the appropriate standards which define additional requirements. (IEC61869-3 VT’s, IEC61869-5 CVT’s). The IEC standards cover only the fundamental system frequency. So far, no studies or information exists on higher frequency ranges, but this knowledge is necessary for reliable and secure network operation.

First publications on the frequency response of HV-voltage instrument transformers investigated the dependency of the accuracy of the system voltage up to 245kV [1]. External influences such as temperature, burden, transformer design and manufacturing variations are published for MV-voltage transformer in [2]. Technical report IEC/TR 61869-103 is published in 2012. This gives guidance on the use of HV instrument transformers for measuring power quality parameters. All the published results show a system voltage dependent behaviour of the frequency response of instrument transformers up to EHV system (see figure 1).

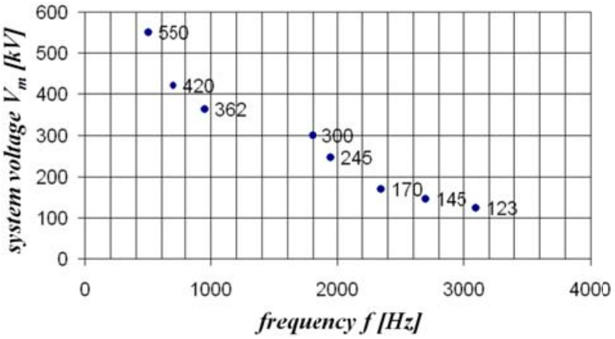


Figure 1: First resonance peak depending on the system voltage V_m [3]

The following aspects have a significant influence on the capacitive part of the resonance circuit and are relevant when considering the frequency response of MV, HV and EHV instrument transformers.

1. voltage dependency (e.g. HV insulation coordination)
2. dependence on ambient conditions (e.g. creepage distance, external service conditions at altitude)
3. basic design (e.g. design for gas or oil insulation)
4. type of measurement (e.g. capacitive “CVT”, inductive “VT”)

In general, the resonance frequency f_R of an instrument transformer depends on a capacitive and an inductive part.

(1)

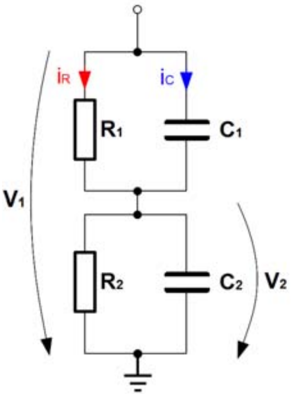
If the capacitive part C is increased, the resonance frequency f_R will decrease if the inductive part L does not change. The frequency response of an instrument transformer is typically characterised by several resonance frequencies. Multiple resonance circuits (parallel circuit as well as series circuit) exist with different capacitances and inductances. An example of a resonance curve for conventional inductive instrument transformers is presented, which illustrates this behaviour.

RESISTIVE-CAPACITIVE-VOLTAGE DIVIDER

The capacitive part of the instrument transformer depends on the voltage level as a result of the dimensioning of the insulation system. It cannot be reduced by a large amount. With reference to equation (1), the inductive part L is the second factor that can be modified in order to change the resonance frequency. The main inductance L_H of a typical inductive voltage transformer can range over several *kH*. A possible solution to these problems is a resistive-capacitive voltage divider, known as a RC-divider. This non-conventional voltage measurement system has no significant inductance.

RC-divider fundamentals

An RC-divider consists of a capacitor divider together with a resistive divider, which are electrically connected in parallel. The simplified equivalent circuit diagram is shown in figure 2. Expected stray capacitances are not considered.



V_1: Primary voltage
V_2: Secondary voltage
C_1: Primary capacitance
R_1: Primary resistance
C_2: Secondary capacitance
R_2: Secondary resistance
i_C: Capacitive current
i_R: Resistive current

Figure 2: Simplified equivalent circuit diagram of a RC-divider

The complex transfer function *k(jω)* of the secondary voltage $\underline{V_2}$ divided by the primary voltage $\underline{V_1}$ is:

$$\frac{\underline{V_2}}{\underline{V_1}} = k(j\omega) = \frac{C_1}{C_1 + C_2 \cdot \frac{(1 + 1/(j\omega C_2 R_2))}{(1 + 1/(j\omega C_1 R_1))}} \tag{2}$$

or

$$\frac{\underline{V_2}}{\underline{V_1}} = k(j\omega) = \frac{R_2}{R_2 + R_1 \cdot \frac{(1 + j\omega C_2 R_2)}{(1 + j\omega C_1 R_1)}} \tag{3}$$

Both formulas indicate that the transfer function characteristic is frequency dependent.

Depending on the angular frequency *ω=2πf*, the following conclusions can be made:

$$f \to \infty \qquad \frac{V_2}{V_1} = \frac{C_1}{C_1 + C_2} \tag{4}$$

$$f \to 0 \qquad \frac{V_2}{V_1} = \frac{R_2}{R_2 + R_1} \tag{5}$$

For high frequencies ($f \to \infty$), the capacitive divider is the dominant part of the transfer function; for very low frequencies down to DC ($f \to 0$), the resistive divider dominates the transfer function.

As shown in figure 2, the system current consists of a resistive part and a capacitive part. Depending on the selection of the resistance values R_1 and R_2 (R-divider) and the capacitance values C_1 and C_2 (C-divider) and also under consideration of frequency and voltage, one of both divider ratios is more dominant than the other. At the crossing point of the current curves, the influence of both dividers on the ratio is equal. At this crossing point the probability of incurring the highest inaccuracy is the highest compared to both extreme points at $f=0$ and $f=\infty$.

Another very important condition can be derived from formulas (2) or (3). The compensation condition demands that the resistive divider ratio has to correspond to the capacitive divider ratio. The time constant τ is defined as an RC term. For a frequency-independent divider ratio of V_2/V_1, up to very high frequency values, the time constant τ_1 of the primary part has to be identical to the time constant τ_2 of the secondary part.

$$\tau_1 = \tau_2 \;\rightarrow\; R_1 \cdot C_1 = R_2 \cdot C_2 \tag{6}$$

Three main system states can be distinguished. Figure 3 shows the system response in the time domain depending on the ratio of the time constants τ_1 and τ_2.

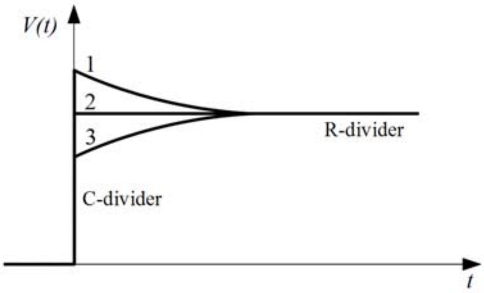


Figure 3: Transient response

1.	$\tau_1 > \tau_2$, Undercompensation
2.	$\tau_1 = \tau_2$, compensated
3.	$\tau_1 < \tau_2$, Overcompensation

In the case of system state 2, the secondary voltage follows the primary voltage with a constant frequency-independent time delay. The divider ratio V_2/V_1 is constant at all times.

Determination of resonance frequency

From the theoretical point of view, there seems to be no limit on the measurement of voltages up to several MHz. With respect to the non-ideal behaviour of the capacitive part C_1, the inductive part L will limit the frequency response behaviour. A method with which the natural frequency can be determined is described in IEC60358. To avoid an additional parasitic inductance, caused by the measuring circuit, a coaxial measuring circuit design should be used. Figure 4 shows the behaviour of the main impedance with respect to the applied frequency.

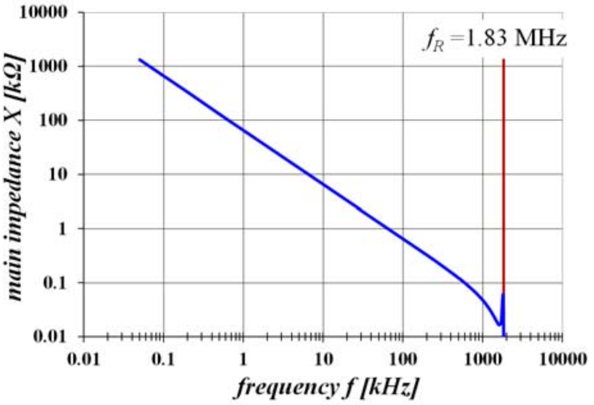


Figure 4: Main impedance curve for a 420kV RC-divider

At resonance frequency, the impedance part X_C is compensated by the impedance part X_L. Only the resistance component is still measurable. According to formula (1) and under consideration of the result obtained for the natural frequency $f_R=1.83MHz$ as well as the main capacitance $C_1=2400pF$, the calculated parasitic inductance within the primary part of the RC-divider is $L_{Para}=3.3\mu H$.

Calculation of voltage error and phase dispacement

In the case of non-equal time constants τ_1 and τ_2, formulas 2 and 3 have to be used for the final calculation of the voltage error ε_U and the phase displacement $\Delta\varphi$.

$$\left|\frac{\underline{Z_{ges}}}{\underline{Z_2}}\right| = 1 + \frac{C_2}{C_1}\sqrt{\frac{1+1/(\omega C_2 R_2)^2}{1+1/(\omega C_1 R_1)^2}} \qquad (7)$$

or

$$\left|\frac{\underline{Z_{ges}}}{\underline{Z_2}}\right| = 1 + \frac{R_1}{R_2}\sqrt{\frac{1+(\omega C_2 R_2)^2}{1+(\omega C_1 R_1)^2}} \qquad (8)$$

The formula for the voltage error ε_U calculation is defined in IEC61869-3, sub-clause 3.4.3 as:

$$\varepsilon_U = \frac{\left|\frac{\underline{Z_{ges}}}{\underline{Z_2}}\right| \cdot V_2 - V_1}{V_1} \cdot 100\ [\%] \qquad (9)$$

The definition of the phase displacement $\Delta\varphi$ can be found in IEC61869-1, sub-clause 3.4.4. It is defined that, in the case of positive phase displacement, the secondary voltage leads the primary voltage.

$$\Delta\varphi = \varphi_2 - \varphi_1 \qquad (10)$$

The phase displacement calculation is defined as:

$$\Delta\varphi = -\arctan(1/(\omega C_2 R_2)) + \arctan(1/(\omega C_1 R_1)) \qquad (11)$$

or

$$\Delta\varphi = \arctan(\omega C_2 R_2) - \arctan(\omega C_1 R_1) \qquad (12)$$

Technical design

The technical designs of RC-dividers are shown in fig. 5.

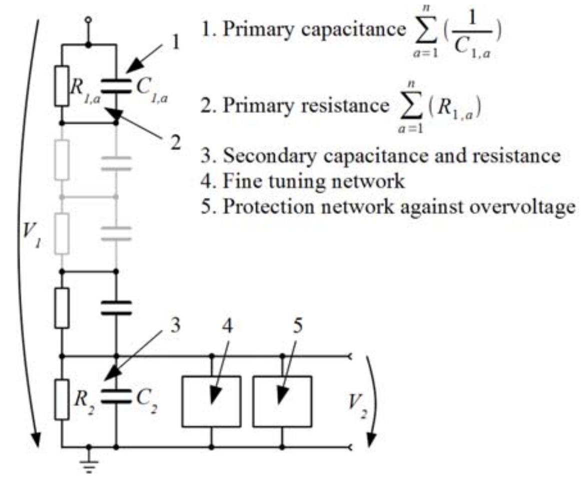


Figure 5: Electrical circuit diagram of a real RC-divider

The primary part consists of single capacitor elements connected in series. Depending on the system voltage the number of single capacitor elements varies. The same requirements are valid for the resistance part. Additionally, power losses during service or during test have a significant influence on the divider design and the number of resistors needed. It is essential to avoid a temperature-dependent inaccuracy. With respect to the divider formula, the resistors on both the primary and secondary sides should have the same temperature coefficient. The same condition is also valid for the capacitance. High temperature differences between the primary and secondary parts of the RC-divider have to be avoided.

MEASURMENTS AND RESULTS

Experimental setup

A single-phase power amplifier provides a test signal up to a voltage level of 280V (RMS) in a frequency range of 15Hz up to 10kHz. The sinusoidal signal was generated by an external generator and transmitted to the power amplifier. The data acquisition was realized using ADC-boards with a sampling rate of 2MS/s. The measurement system used, including all components and necessary sampling rates, were discussed in detail in a former paper [1].

Test method

The test starts at a predefined frequency of 15Hz with incremental steps up to the maximum frequency of 10kHz. Initially, the step width was changed in an adaptive manner in order to determine possible resonance frequencies. Later, with respect to the initial results and the analyses of the data, more efficient frequency steps were used. Test conditions were:

1. A 420kV RC-divider in an upright position
2. Test voltage, applied to the primary terminal was realized using a coaxial cable
3. Rated burden connected to the secondary terminals.
4. Test voltage directly measured at the primary terminal
5. Coaxial conductors used for all measurement cables

6. Earthing was realized as a star-point connection to prevent inductive loops.

For each frequency, the primary voltage V_1 divided by the nominal ratio n (green curve in figure 6) and the secondary voltage V_2 (red curve in figure 6) were measured simultaneously.

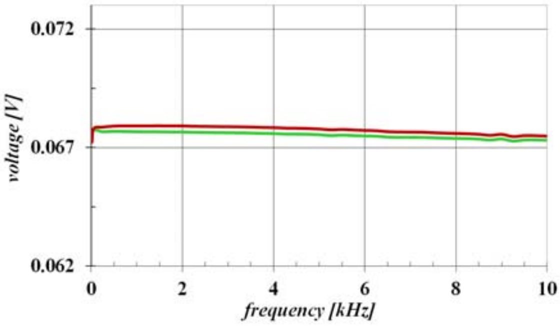


Figure 6: Magnitude of measured voltage V_1/n (green), V_2 (red)

Results

Based on international rules on the display of accuracy for instrument transformers (see formula 9), the frequency-dependent voltage error and phase displacement are shown in figure 7.

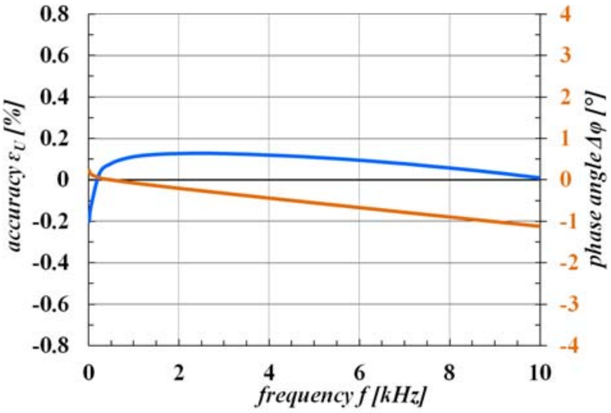


Figure 7: Frequency response of voltage accuracy $\square_U(f)$(blue) and phase displacement Δφ(f)(orange)

The characteristic of the voltage error $\square_U$ (blue curve), shows that the RC-divider has no resonance frequency in the measured frequency range. The accuracy obtainable is within ±0.2% over the complete range. The phase displacement over the frequency range is displayed in orange. The phase displacement error is low enough for the identification of the direction of the spurious signal sources. Several series of measurements confirmed the findings stated. The accuracy achievable in comparison to conventional inductive instrument transformers is very high and stable up to a frequency of 10kHz.

The frequency response of different instrument transformers for HV and EHV voltage levels is shown in figure 8. All conventional instrument transformers have resonance frequencies with very high accuracy errors in the frequency range up to 10kHz. Only the RC-divider shows a linear frequency response (see blue line in fig 7).

The accuracy results were measured with the same test system, test method and under the same test conditions as described above. No burden was connected to these conventional instrument transformers.

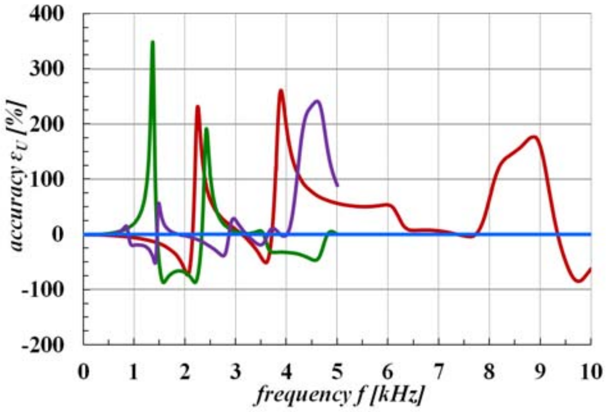


Figure 8: Frequency response of voltage accuracy $\varepsilon_U(f)$ for 123kV-VT(red), 245kV-VT(green), 420kV-CTVT(purple) and 420kV-RC-divider (blue); measured at the PFIFFNER company.

DISCUSSION

This paper is a contribution to discussions on the possibilities of measuring harmonic voltages in the power network using a RC-divider with a very high accuracy up to the 200th harmonic of the rated frequency f_N. The theoretical aspects described as well as the technical solutions derived explain the behaviour of this kind of non-conventional measurement system. The results of accuracy measurements verify the theoretical considerations.

In comparison with conventional inductive instrument transformers with their resonances, this technical solution has the potential of measuring harmonics to a high level of accuracy up to very high frequencies for HV and EHV voltage levels.

Further aspects, like temperature and voltage dependencies, long-term behaviour or proximity influences on accuracy should be investigated in more detail. First test results also confirm the expected performance of the RC-divider.

Up to now, international definitions of accuracy classes for higher frequencies exist, but reasonable and sensible classes are still needed. A second very important aspect is the definition of the harmonic frequency range necessary. Until now, the 50th harmonic is mentioned in international standards for MV, HV and EHV networks (e.g.IEC61000-3-6). Discussions concerning harmonics up to the 200th of f_N are becoming more and more important.

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