Frequency response analysis to assess the application bandwidth of inductive voltage transformers

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Abstract

The accuracy of instrument voltage transformers for power quality measurements must be guaranteed up to higher frequencies. Currently, voltage transformers are only calibrated for rated frequency. Technically sophisticated measurement setups are required to measure the standardized voltage ratio error up to higher frequencies. Accurate measurements require the voltage transformer to be magnetized both with the fundamental component and the higher frequency component. On-site measurements of the frequency-dependent transfer characteristics of voltage transformers are motivated by the fact that the burden significantly influences the measurements. The aim of this paper is to find practical methods for this application, especially suitable for on-site use and to discuss the accuracy and robustness of the introduced method. For that purpose, adequate parameters must be defined that can be used to qualify the devices for higher frequency measurements. In addition, it is aimed to utilize measurement technologies that are already known and established in the power industry. In this paper, the application bandwidth of instrument voltage transformers is discussed as a parameter to qualify the device for higher frequency applications such as power quality measurements. Well-known *Sweep Frequency Response Analysis* is qualified in this paper, if it can be utilized to determine the application bandwidth of instrument transformers accordingly.

1. Introduction

For power quality (PQ) measurements in electrical energy grids, the whole measurement chain must be considered to provide accurate measurements. The measurement chain for voltage measurements consists of conventional or low power instrument voltage transformers and the measurement instrument including all connections in between. Inductive instrument voltage transformers (VTs or IVTs) are used to transform the high system voltage to a proportional and measurable quantity. The transfer characteristics of the VTs should be linear up to the frequency to be measured. As soon as the VT shows a nonlinear transfer characteristic, the measured data are falsified, even if the PQ instrument fulfills a certain accuracy class. As conventional VTs are typically used to connect PQ instruments on the one hand but have a nonlinear transfer characteristic on the other hand, the frequency dependent transfer characteristics and thus the application bandwidth of VTs must be tested to guarantee accurate measurements. From testing perspective, there is a conflict between a) available testing technology, b) nonlinearity of instrument transformers, c) applicability for the end user and finally d) cost effectiveness. This conflict is mainly caused by the fact, that the fundamental magnetization is required in addition to the high frequency component to achieve highly accurate measurements causing extensive test setups [1].

In this paper, the applicability of well-established and commonly available testing technology *Sweep Frequency Response Analysis* (SFRA) to measure the frequency dependent transfer characteristics of VTs and hence to quantify an application bandwidth of the devices under test is investigated. According to [2], it is recommended to define 1%, 5% and 10% application bandwidths for VTs to qualify the VT applicability for PQ measurements. This approach is based on the idea to introduce critical frequencies for VTs [3] and on the empirical qualification presented in the Cigré Technical Brochure 596 [4].

2. Methodology

As the transfer characteristics of VTs is burden dependent [5], standardized SFRA measurements terminated with 50 Ω are compared against a modified high impedance SFRA measurement with 1 MΩ termination on different VTs to identify the influence of the measurement equipment. This step underlines the importance of a high impedance measurement input and the consideration of the connected burden in related studies and (field) measurements. Secondly, the absolute and relative application bandwidths (cf. [2]) are introduced as measurands for the investigations and parameters to qualify VTs for higher frequency PQ measurements.

In a third step, the high impedance 1 MΩ SFRA measurement is compared against reference laboratory

measurements to investigate the applicability of SFRA technology for this application. Based on the investigations, a test methodology is presented how to utilize SFRA measurements for the intended application. In these regards, the introduced relative application bandwidth of instrument transformers as a qualitative measure to describe the VT applicability for higher frequencies is considered and measured for several medium and high voltage VTs.

3. Measurement Technologies

SFRA – Sweep Frequency Response Analysis

SFRA is commonly used in the field of diagnostics of electric power equipment such as power transformers [6]. SFRA uses a low voltage (10 V peak-peak) measurement method with frequencies up to 30 MHz to obtain the frequency response of a given system. As the measured secondary voltage and thus the input signal for the measurement device is small (dependent on the VT ratio), the measurement system needs to be shielded. The test voltage of SFRA technology may limit the application range in terms of VTs to a certain ratio due to the signal magnitudes. The input impedance of commercially available SFRA devices is 50 Ω. As this value is lower than the typical impedance of a connected PQ instrument, these measurements are compared against measurements with a redesigned device with 1 MΩ input impedance, see Fig. 1.

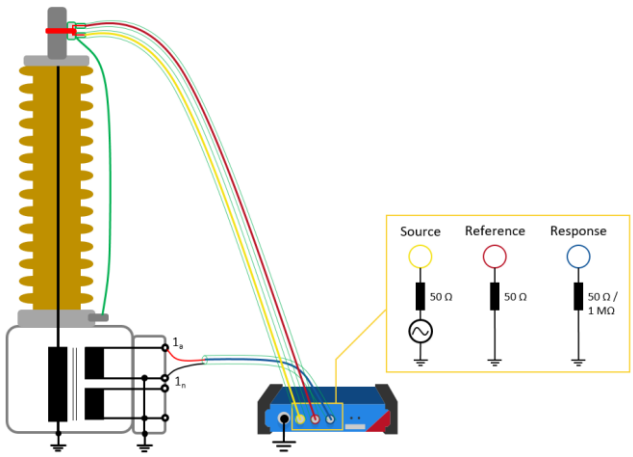

Fig. 1: Measurement setup SFRA

Specifications of SFRA measurement device:

- Frequency range 1 Hz…30 MHz
- Source output: Amplitude 10 V_{pp} at 50 Ω
- Dynamic range >150 dB (+10 dB…< –140 dB noise floor RMS)
- Accuracy in the frequency range 20 Hz…2 MHz Attenuation 0 dB…–50 dB (±0.1 dB – Typical) (±0.3 dB – Guaranteed) –50 dB…–100 dB (±0.3 dB – Typical) (±0.5 dB – Guaranteed)
- Frequency accuracy 20 Hz…30 MHz 0.02%

Reference Test Setups

SFRA measurements are compared with two-frequency reference measurements with a laboratory setup (Fig. 2). The concept of two-frequency measurement has also been adapted in a mobile test device [7]. The two-frequency method including a fundamental magnetization has been established for measurements of the frequency dependent transfer characteristics of inductive voltage transformers in former investigations, e.g. [1, 5, 7]. With the laboratory test setup, a sinusoidal voltage with variable magnitude (up to the rated value) and rated frequency is generated by the HV-Transformer and the harmonic signals are superposed with a MV-Transformer. A calibrated capacitive divider is used as the reference. [5, 7]

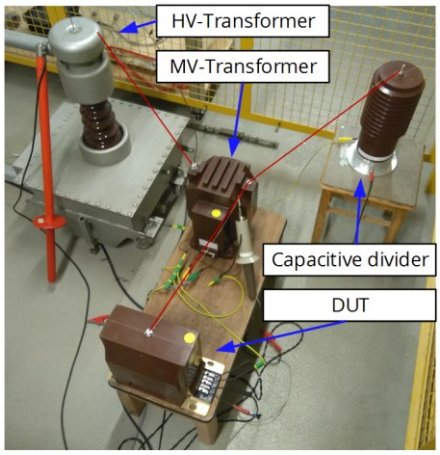

Fig. 2: Reference measurement setup

The mobile reference test device also uses the two-frequency method but with lower magnitudes of the fundamental signal and presents a confirmed deviation from the reference setup by less than 1 % [7].

4. Application bandwidth

As displayed in Fig. 3, the application bandwidth is defined as the frequency range in which a VT maintains a certain accuracy (i.e., 1%, 5%, 10%) that is still appropriate for the intended application and can be selected by the user [2]. It is expressed by the highest frequency for which the respective accuracy is still met ($f_{\mathrm{app}\ x\%}$).

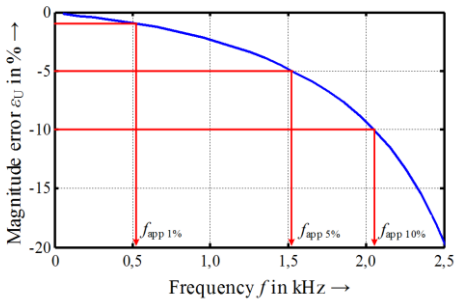

Fig. 3: Definition of absolute application bandwidth [2]

The application bandwidth can be distinguished between absolute and relative application bandwidth. The absolute application bandwidth is defined as the frequency, where the voltage ratio deviates from the rated voltage ratio of the VT by a specified value, i.e. ±(1, 5, 10)% (Fig. 3). The relative application bandwidth is defined as the frequency where the measured voltage ratio is deviating ±(1, 5, 10)% from the measured voltage ratio at rated frequency (**Error! Reference source not found.**). The rel. application bandwidth indicates, at which frequency the DUT measures 1%, 5% or 10% less accurate compared to rated frequency. It is systematically influenced by the impact of the fundamental magnetization on the frequency-dependent transfer characteristics of VTs.

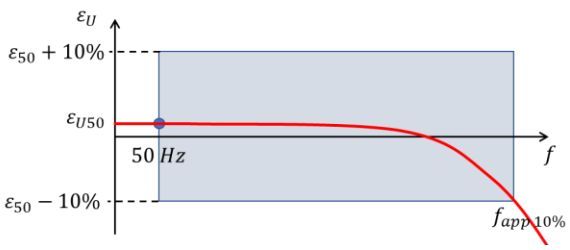

Fig. 4: Definition of 10% relative application bandwidth

5. Laboratory experiments

5.1. Comparison of SFRA measurements with 50 Ω and 1 MΩ termination

In Fig. 5, the voltage ratio error differences between SFRA measurements with 50 Ω and 1 MΩ termination are presented exemplarily for four VTs. 1 MΩ results are used as reference.

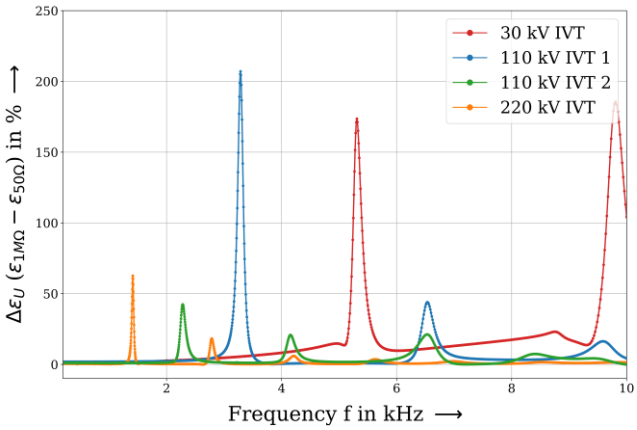

Fig. 5: Voltage ratio error difference between SFRA measurements with 50 Ω and 1 MΩ termination

These results clearly underline the importance to consider the connected burden for measuring the frequency-dependent transfer characteristic of VTs (cf. [5]). The frequency range around the resonance frequencies is deviating significantly. The off-the-shelf SFRA measurement device with 50 Ω termination cannot be used for the intended application as it falsifies the measurement results due to the wrong representation of the burden impedance found on site. 50 Ω equals a burden of 66 VA at 100/√3 V which is typically significantly larger than the connected burden on site. Consequently, only the modified SFRA measurement with 1 MΩ termination is suitable for further investigations (except the use case in chapter 5.4).

5.2. Comparison of 1 MΩ SFRA measurements with laboratory reference

The SFRA measurement terminated with 1 MΩ is compared with the two-frequency (2Freq) reference setup described in section 3. In Fig. 6, the results are displayed for a 35 kV medium voltage VT. The amplitude of the fundamental component of the test signal varies between rated voltage (20,2 kV), 260 V and zero (SFRA measurement). The harmonic component is set to 5% of the fundamental amplitude for the two-frequency measurements and 10 V_{pp} for the SFRA measurement respectively. As shown in Fig. 6, the difference between the measurements seems systematic and linear in the interesting frequency range reflecting the application bandwidth ($\varepsilon_U \leq 10\%$).

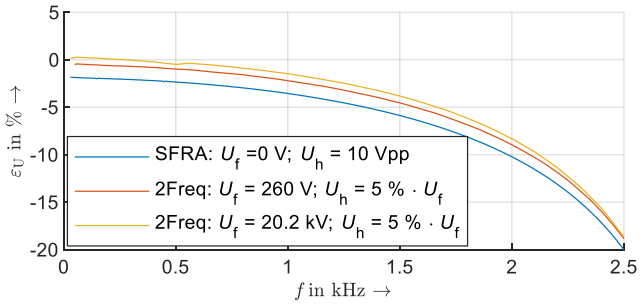

Fig. 6: Frequency dependent ratio error of a 35 kV VT, measured with 2Freq reference measurements and high impedance 1MΩ SFRA

The results show a significant difference between the three applied methods and confirm that the absolute voltage ratio error is sensitive on the fundamental magnetization of the VT. This behaviour confirms former studies, e.g. [1]. The results already indicate that SFRA measurements cannot be used to determine the absolute voltage ratio error. However, as the difference between SFRA and reference measurement is almost linear (this has been verified on the medium voltage VTs in Table 1), 1 MΩ SFRA technology can be used to identify the relative application bandwidth (see section 5.3). Here, the frequency with 1%, 5% or 10% voltage ratio error difference to the ratio error measured at rated frequency is determined, which is independent on the accuracy of the ratio error at rated frequency. The latter may be calibrated with an additional calibration measurement.

5.3. *Absolute vs. relative application bandwidth*

The relative application bandwidth is compared to the absolute application bandwidth, both determined with the reference setup and the two-frequency test signal. Furthermore, SFRA results are used to evaluate the measurement technology and the robustness of the newly introduced parameters of relative and absolute application bandwidth. Table 1 gives an overview about the determined application bandwidths.

Table 1: Absolute and relative application bandwidth in Hz determined with reference setup and 1 MΩ SFRA

DUT	Appl. Bandwidth	Meas. System	No burden			Rated burden		
			1%	5%	10%	1%	5%	10%
10 kV IVT	Abs.	SFRA	2140	10519	11742	269	3192	5143
		Ref.-Sys	9453	>10000	>10000	1429	3518	5285
	Rel.	SFRA	2742	10503	11744	950	3457	5319
		Ref.-Sys	4148	>10000	>10000	1440	3524	5290
20 kV IVT 1	Abs.	SFRA	-	2987	4149	-	1621	2629
		Ref.-Sys	1760	3381	4313	730	1911	2778
	Rel.	SFRA	1564	3358	4318	893	2034	2882
		Ref.-Sys	1445	3268	4258	793	1938	2796
20 kV IVT 2	Abs.	SFRA	174	3436	4629	-	1815	2851
		Ref.-Sys	1924	3708	4687	889	2103	2986
	Rel.	SFRA	1355	3672	4732	638	2085	3012
		Ref.-Sys	1633	3608	4641	950	2129	3003
35 kV IVT	Abs.	SFRA	-	1346	1982	-	940	1557
		Ref.-Sys	843	1668	2122	390	1206	1688
	Rel.	SFRA	754	1634	2111	576	1273	1736
		Ref.-Sys	757	1639	2108	463	1242	1709

With the reference setup, the ratio error at rated frequency and higher frequencies is accurately determined. As VTs are typically very accurate at rated frequency (e.g. ≤ 0,2%), 5% and 10% absolute and relative application bandwidth are virtually similar using the reference setup. The 1% application bandwidth is more sensitive to the measurement technology. Using the SFRA, absolute and relative application bandwidth vary more significantly due to the missing fundamental component and the higher deviating ratio error at rated frequency. However, the 5% and 10% relative application bandwidths determined with SFRA and the reference setup are comparable.

The relative application bandwidth as the performance parameter can be accurately determined with 1 MΩ SFRA technology. Instead of accurate measurement of the ratio error itself, this method is suitable to accurately determine a less sensitive application bandwidth. This methodology provides significant advantages regarding on-site use as no sophisticated test setups are needed to get reliable information about the application range of a VT.

5.4. *Empirically determined application bandwidth from first resonance maximum*

As introduced in [2], the application bandwidth can also be determined empirically based on the first resonance frequency. SFRA allows to accurately determine the first resonance frequency and thus, this technology may be used in addition with an empirically determined ratio f_{app}/f_{res} to derive the application bandwidth. For the DUTs in Table 1 and the f_{app}/f_{res}-ratios defined in [2], the empirically determined application bandwidth is shown in Table 2 next to the respective first resonance frequencies and the relative application bandwidth determined with 1 MΩ SFRA. This methodology provides an alternative way to determine the

application range. The used ratios f_{app}/f_{res} based on the 5% percentile (cf. [2]) represent a worst-case scenario. Compared to Table 1 (no connected burden), the results presented in Table 2 typically provide more conservative results. As the determined first resonance frequencies are even comparable between the 50 Ω SFRA and the 1 MΩ SFRA, both SFRA devices can also be used to determine the empirically based application bandwidth.

Table 2: Empirically determined application bandwidth (here: Empirical bandwidth) and first resonance frequencies using SFRA compared to the relative application bandwidth of Table 1 (no burden)

1st resonance frequencies	10 kV IVT	12369 Hz		
	20 kV IVT 1	6668 Hz		
	20 kV IVT 2	6679 Hz		
	35 kV IVT	3242 Hz		
Application Bandwidth		1%	5%	10%
Empirical ratio from [2]		0.11	0.43	0.56
10 kV IVT	Empirical bandwidth	1360 Hz	5319 Hz	6926 Hz
	Relative App.-bandwidth	2140 Hz	10519 Hz	11742 Hz
20 kV IVT 1	Empirical bandwidth	733 Hz	2867 Hz	3734 Hz
	Relative App.-bandwidth	-	2987 Hz	4149 Hz
20 kV IVT 2	Empirical bandwidth	734 Hz	2872 Hz	3740 Hz
	Relative App.-bandwidth	174 Hz	3436 Hz	4629 Hz
35 kV IVT	Empirical bandwidth	357 Hz	1394 Hz	1816 Hz
	Relative App.-bandwidth	-	1346 Hz	1982 Hz

6. Field measurements

The high impedance 1 MΩ SFRA measurements have been used to determine the relative application bandwidth of 47 medium and high voltage VTs. The measurements have been performed on-site, at manufacturers and in storehouses of network operators. The measurements have been performed without any connected burden to the VTs. The results are displayed in Fig. 7 and Fig. 8. The 1%, 5% and 10% application bandwidths are displayed in the figures, grouped depending on the rated primary voltage of the VTs. Every displayed measurement point displays the particular application bandwidth of one VT.

It must be considered that the burden influences the application bandwidth. Thus, it is recommended to perform such measurements either with connected standard burdens or on site in the original installation environment. If the VT is exclusively used for PQ measurements, the measurements without connected burden may be more representative due to high input impedances of PQ instruments.

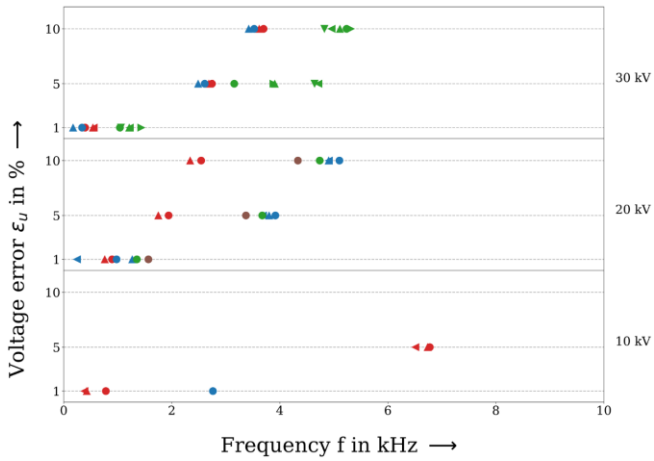

Fig. 7: Application bandwidth of medium voltage VTs determined with 1MΩ SFRA

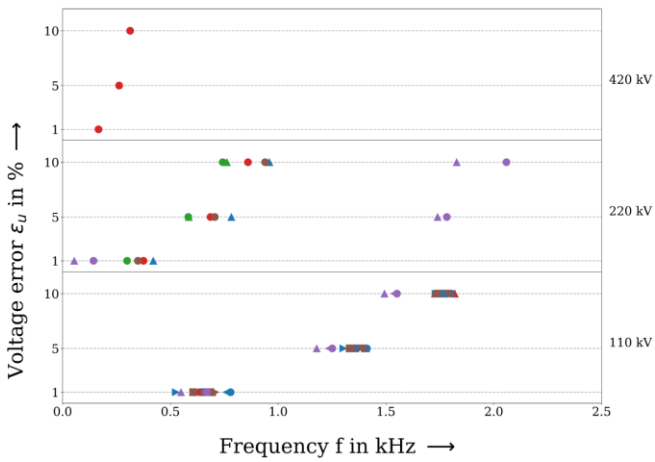

Fig. 8: Application bandwidth of high voltage VTs determined with 1MΩ SFRA

Depending on the primary voltage, clear patterns can be recognized, especially for high voltage VTs. The tested medium voltage VTs show larger variance. It must be noted that the 1% application bandwidth shows a high sensitivity on the measurement method and thus the results should be interpreted with care (cf. Table 1).

7. Summary

In this paper, Sweep Frequency Response Analysis has been qualified to test the frequency-dependent transfer characteristics of inductive voltage transformers. It has been shown that this measurement technology can be used to reliably determine the application bandwidth based on a relative method or based on empirically derived 'resonance to application ratios'.

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