On-site Calibration of Voltage Transformers

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Abstract— **The accuracy classes of voltage transformers (VTs) are different for protection and metering transformers and are classified depending on the maximum ratio and phase-angle error between the vectors of the primary voltage and the secondary voltage. If instrument transformers are not within their defined standard specifications anymore there is a risk of incorrect meter readings and ineffective or even failing system protection. Especially when in aged condition, it is therefore advisable to routinely assess the condition of instrument transformers in order to ensure safe operation within defined standard limits and tolerances. In this context, different methods are discussed in literature to calibrate VTs in a laboratory or on-site. Lately, an autarkic on-site calibration approach was proposed [1]. This paper presents a practical point of view of the newly proposed method for on-site calibration of inductive and capacitive voltage transformers [1] by using a so called modeling approach. Following [1], the VT is considered as a black-box whose parameters according to the equivalent circuit diagram have to be obtained by utilizing low voltage measurements from both the primary and secondary side. Once the parameters are known the performance of the VT can be calculated and assessed using a mathematical model even up to its rated primary voltage and beyond. The new method has been verified in field studies on new and aged capacitive and inductive VTs. As a result, the investigation shows high accuracy and high reproducibility using the discussed model. This method allows conducting on-site calibration of VTs with low voltage signals and thus reducing weight of test equipment and time for testing.**

Keywords—inductive voltage transformer, instrument transformer, on-site calibration, modeling approach

I. INTRODUCTION

To date the accuracy of conventional voltage transformers have mostly been obtained by applying rated voltage at the primary side and measuring the resulting secondary voltage, while rated load is applied, either in a laboratory or on-site. Due to the high voltage needed for such tests, this method has its practical limits, especially when it comes to on-site testing, respectively commissioning testing.

A new approach for measuring the voltage and load depending voltage ratio error and phase displacement is the so called "modeling approach" [1].

This paper discusses the applicability of this alternative approach and points out the information needed for calculating the voltage ratio error and phase displacement. Furthermore, some case studies from conducted field tests are presented.

II. ACCURACY REQUIREMENTS FOR VOLTAGE TRANSFORMERS

International standards specifying the accuracy definition and its limitation for conventional voltage transformers such as

- IEC 60044-2 for inductive voltage transformers
- IEC 60044-5 for capacitive voltage transformers
- IEC 61869-3 additional requirements for inductive voltage transformer (successor of IEC 60044-2)
- IEC 61869-5 additional requirements for capacitive voltage transformers (successor of IEC 60044-5)
- IEEE C57.13 standard requirements for instrument transformers
- ANSI C93.1 requirements for power-line carrier coupling capacitors and coupling capacitor voltage transformers (CCVT)

For metering windings the voltage ratio error and phase displacement is specified in between 80 % to 120 % (IEC) resp. 90 % and 110 % (IEEE) of the rated primary voltage and from 25% to 100% of the rated secondary burden. In addition for class 0.1 and 0.2 having a rated burden of 10VA or lower, the current ratio error and phase displacements is defined even for 0VA, representing an open circuit (IEC).

For protection windings the voltage ratio error and phase displacement is specified even from 2 % up to 100 %*F_v of the rated primary voltage, whereas F_v is the rated voltage factor and can be specified up to 1.9 times of rated primary voltage. The burden range is specified from 25% to 100% of rated burden.

Furthermore for voltage transformers having more than one secondary winding the accuracy has to be fulfilled while other windings have to be treated as both, open circuit (0VA) and loaded with 100% rated burden under consideration of the defined total simultaneous burden.

III. MODELING APPROACH

For a proper modeling approach the internal parameters of a voltage transformer have to be determined [1]. The parameters are:

- Primary and secondary leakage reactance
- Primary and secondary winding resistance
- Excitation curve at rated frequency

In addition the turns ratio of the voltage transformer under test has to be measured for considering a possible turns ratio compensation. A turns ratio compensation is a common practice for compensating the voltage ratio error towards a more positive ratio error. Using this method it can be achieved that the voltage transformer will stay within the tolerances defined by its accuracy class.

For the determination of the individual parameters several tests have to be conducted. Therefore the measurement procedure utilizing the modeling approach is as follows:

A. Measurement of short-circuit impedances

B. Measurement of secondary winding resistances

C. Measurement of secondary short-circuit impedance (in case of more than one secondary winding)

D. Measurement of the initial magnetization curve and separation of frequency dependent core losses

E. Measurement of the turns ratio

With the information of above tests the load dependent voltage ratio error and phase displacement can be calculated accordingly.

IV. Case Studies

A. *Measurement on a 66 kV reference VT*

The first case study is about an on-site measurement on a 66 kV to 132 kV reference VT. The secondary winding has two taps for adapting the ratio between 132 kV/$\sqrt{3}$:110 V/$\sqrt{3}$ and 66 kV/$\sqrt{3}$:110 V/$\sqrt{3}$. The nameplate information about the VT is indicated in Fig. 1. The accuracy of this reference VT is defined as ±0.03 % in voltage ratio error and ±1.5 min in phase displacement at a rated load of 1 VA with a power factor of 1.0 and for a voltage range from 50 % to 125 % of rated primary voltage. The accuracy of the VT is specified for a frequency range of 50 Hz to 60 Hz.

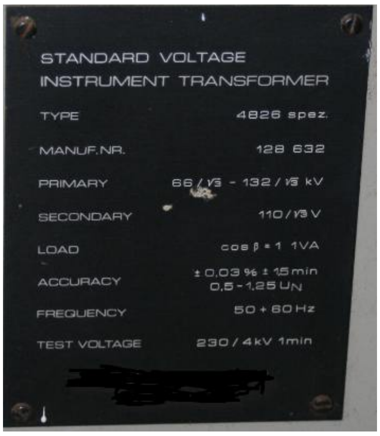

Fig. 1. Nameplate of reference VT

Fig. 2 shows the terminal box of the secondary winding. The VT was tested several times in order to prove the stability of the test results for 50 Hz, 60 Hz and even for both possible voltage ratios.

Fig. 2. Secondary terminal box

The test results below are an example for the full tap (66 kV/$\sqrt{3}$:110 V/$\sqrt{3}$) at 50 Hz. It can be seen (Fig. 3 and Fig. 4) that the voltage ratio error is within the required limits of ±0.03 % from 80 % up to 120 % of rated primary voltage and from 0 VA up to 1 VA load condition.

Power			Voltage ratio error in % of rated voltage		
VA	VA [%]	cos phi	80%	100%	120%
1,0000	**100,0%**	**1,0000**	**-0,0064%**	**-0,0038%**	**-0,0019%**
0,0000	**0,0%**	**1,0000**	**-0,0052%**	**-0,0025%**	**-0,0006%**

Fig. 3. Voltage ratio error table

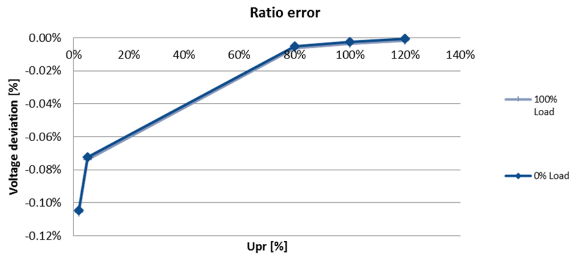

Fig. 4. Voltage ratio error diagram

The obtained phase displacement was slightly outside the required limits of ±1.5 min, see Fig. 5 and Fig. 6. The highest variance was at 80 % rated primary voltage and 1 VA load with an absolute value of -1.07 min. This discrepancy would be acceptable for verification measurements on class 0.1 metering VTs since class 0.1 metering VTs are allowed to have a phase displacement of ±5 min.

Power			Phase displacement table (min)		
VA	VA [%]	cos phi	80%	100%	120%
1,0000	**100,0%**	**1,0000**	**-2,5727**	**-2,5655**	**-2,5576**
0,0000	**0,0%**	**1,0000**	**-2,3296**	**-2,3225**	**-2,3146**

Fig. 5. Phase displacement table

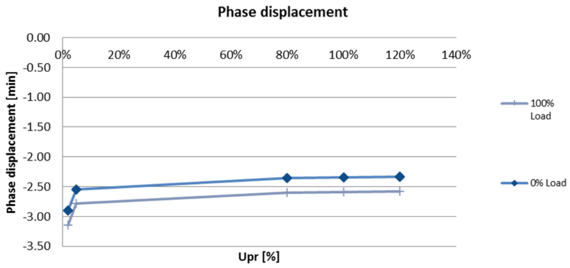

Fig. 6. Phase displacement diagram

The results itself have proven to be very stable over the frequency range of 50 Hz to 60 Hz and for all successive measurements conducted. The highest absolute variance between all successive tests was ±0.001 % in regards to the voltage ratio error and ±0.03 min in regards to the phase displacement.

This proves that the modeling concept works in a reliable and repeatable way.

B. *Measurement on a 4 kV reference VT*

The second case study is about a comparison measurement on a 4 kV cast resin VT. The VT has been calibrated at an independent calibration laboratory in Austria which is traceable to national standards, which realize the physical units of measurement according to the International System of Units (SI). The extended measurement uncertainty U_{Fu} for the voltage ratio error is 0.006 %, respectively $U_{\delta u}$ for the phase displacement is 0.4 min.

Fig. 7 shows the nameplate information of the reference VT and 0 illustrates the obtained voltage ratio error and phase displacement obtained at the laboratory.

Kenndaten:
Characteristic values

Bemessungs-Isolationspegel in kV *Rated Insulation level in kV*	7,2 / 20 / 60
Bemessungsfrequenz in Hz *Rated Frequency in Hz*	50 / 60
Primäre Bemessungsspannung in V *Rated primary Voltage in V*	4000
Sekundäre Bemessungsspannung in V *Rated secondary voltage in V*	100
Bürde in VA cosβ=1 *Burden in VA cosβ=1*	1
Genauigkeitsklasse *Accuracy class*	0,1
Wicklungsbezeichnung *Winding marking*	a - n

Fig. 7. Nameplate information

The obtained test results using the modeling approach in regards to the voltage ratio error and phase displacement are shown in Fig. 9 to Fig. 12. The test had been conducted at a frequency of 50 Hz and 60 Hz.

At 100 % of rated primary voltage and 100 % of rated load the absolute difference in regards to the reference is 0.0042 % in voltage ratio error and 0.75 min in phase displacement.

Ergebnisse der Kalibrierung:
Results of calibration

Die Ergebnisse gelten für die Messwicklung(en) a - n bei einer Frequenz von 50Hz und 60Hz.
The results are valid for the measuring winding(s) a – n at the frequency 50Hz and 60Hz.

Primäre Bemessungsspannung/ *Rated primary voltage*	U/U_N [%]	Sek. Bürde / *sec. Burden: 10 kΩ (=1VA cosβ=1)* Messwicklung / *measuring winding: a - n* — Sekundäre Bemessungsspannung / *Rated secondary voltage* 100 [V]			
		50 Hz		60 Hz	
		F_u [%]	δ_u [']	F_u [%]	δ_u [']
4 [kV]	120	- 0,019	+ 2,7	- 0,011	+ 1,3
	100	- 0,016	+ 2,1	- 0,012	+ 1,1
	80	- 0,016	+ 1,8	- 0,017	+ 0,9
	60	- 0,023	+ 1,7	- 0,025	+ 0,8
	40	- 0,045	+ 1,6	- 0,048	+ 0,9
	20	- 0,093	+ 2,1	- 0,101	+ 1,3

Primäre Bemessungsspannung/ *Rated primary voltage*	U/U_N [%]	Sek. Bürde / *sec. Burden: 0 Ω* Messwicklung / *measuring winding: a - n* — Sekundäre Bemessungsspannung / *Rated secondary voltage* 100 [V]			
		50 Hz		60 Hz	
		F_u [%]	δ_u [']	F_u [%]	δ_u [']
4 [kV]	100	0,000	+ 2,5	+ 0,005	+ 1,6

Fig. 8. Voltage ratio error and phase displacement

At 100 % rated primary voltage and 0 VA load the absolute difference is 0.0062 % in regards to the voltage ratio error and 0.703 min in phase displacement.

The red lines in both diagrams (Fig. 10 and Fig. 12) indicate the absolute allowed error limit according to IEC 60044-1 standard.

Power			Voltage ratio error in % of rated voltage		
VA	VA [%]	cos phi	80%	100%	120%
1,0000	**100,0%**	**1,0000**	**-0,0101%**	**-0,0118%**	**-0,0178%**
0,0000	**0,0%**	**1,0000**	**0,0063%**	**0,0046%**	**-0,0014%**

Fig. 9. Voltage ratio error table

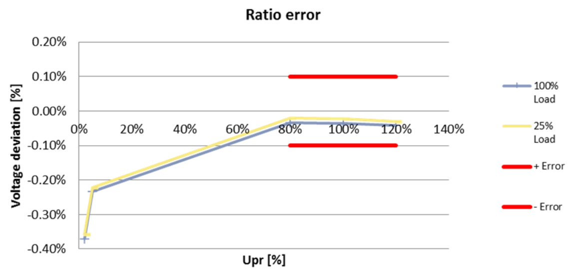

Fig. 10. Voltage ratio error diagram

Power			Phase displacement table (min)		
VA	VA [%]	cos phi	80%	100%	120%
1,0000	**100,0%**	**1,0000**	**1,0573**	**1,3540**	**1,7354**
0,0000	**0,0%**	**1,0000**	**1,4998**	**1,7966**	**2,1781**

Fig. 11. Phase displacement table

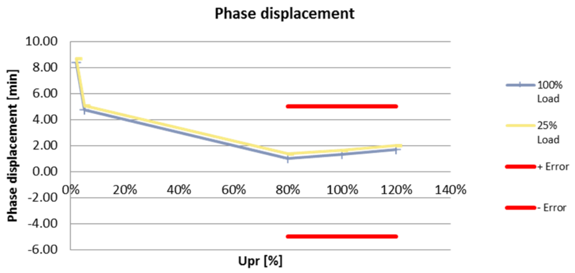

Fig. 12. Phase displacement diagram

C. *Measurement on a 110 kV VT with high rated load*

The third case study is about an on-site measurement on an 110kV inductive VT which is designed for very high load conditions. In Figure 13 the nameplate of the VT is illustrated.

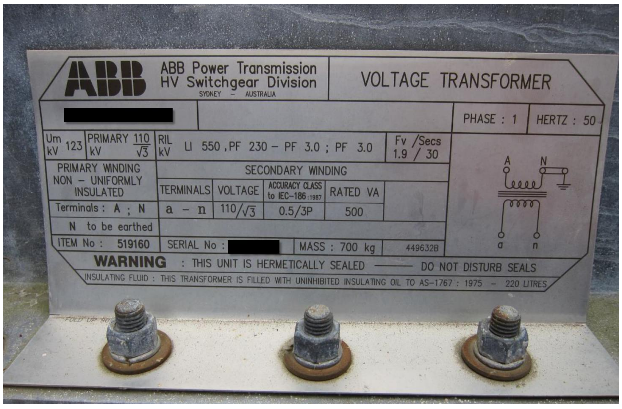

Fig. 13. Nameplate information

The VT has one secondary winding which is used for both metering and protection purposes at the same time. The rated load of the secondary winding is 500VA.

In Figure 14 the voltage ratio error for 100% and 25% of the rated load is shown. In both cases the VT was within its accuracy requirements for a class 0.5 metering VT.

When simulating, resp. recalculating the voltage ratio error for the operating burden (load actually connected to the VT in the field) the VT does not pass the class assessment, see Figure 15. The reason for this is the very low operating burden of just 0.02VA. The VT is designed for high load conditions, thus it has a so called turns ratio compensation. Such VTs can introduce a too positive ratio error at very low load conditions.

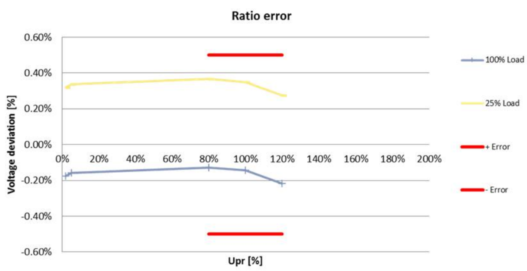

Fig. 15. Voltage ratio error at 100% and 25% of rated load

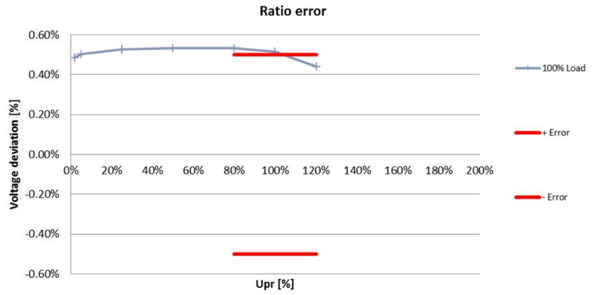

Fig. 14. Voltage ratio error at operating load (0.02VA) conditions

V. Conclusion

This paper discusses the practical application of a newly proposed methodology for mobile resp. on-site testing of inductive voltage transformer. This methodology can be applied on capacitive voltage transformers in a comparable way by simply adding some measurements to obtain the transformation ratio. In order to calculate the load dependent voltage ratio error and phase displacement all parameters according to the equivalent circuit diagram of a voltage transformer needs to be obtained.

The selected case studies have proven that the new approach is feasible. It results in quite accurate test results which are fairly close to the reference obtained from a laboratory calibration. Therefore the device can be used for testing VTs during the manufacturing process and as well for on-site verification of the voltage transformer's accuracy.

Nevertheless, voltage transformers should be tested once with high primary voltages before putting in service, since insulation faults for instance might not be detected by a modeling concept using low voltage and low frequency signals.

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