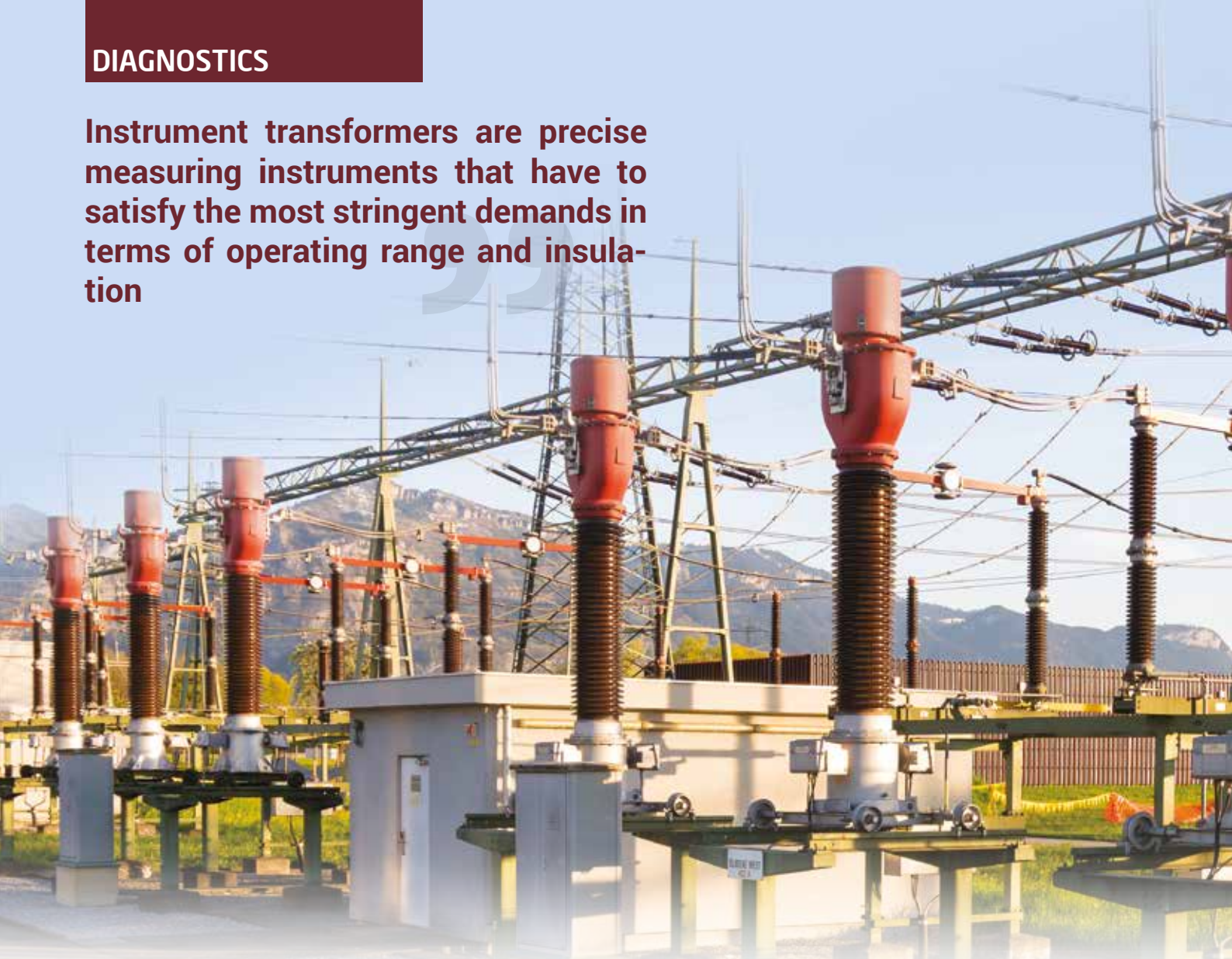Instrument transformers are precise measuring instruments that have to satisfy the most stringent demands in terms of operating range and insulation

ABSTRACT

Instrument transformers for medium- and high-voltage applications play a key role in energy supply. Acting as the link between the primary network and the metering or protection equipment connected to the secondary side, a safe and reliable operation without failures is essential. In relation to this background, this paper discusses testing and diagnostic methods for instrument transformers. Different application examples are presented that help to ensure an efficient production process at the manufacturing site and efficient on-site testing for site acceptance, commissioning or regular maintenance.

KEYWORDS

calibration, commissioning, diagnostics, instrument transformer, testing

Testing and diagnostics of medium- and high-voltage instrument transformers

1. Introduction

The importance of the testing and diagnostics of instrument transformers (transformers used for protection and measuring purposes) is all too often underestimated. Although the cost of instrument transformers (ITs) is relatively low, their correct and uninterrupted operation is an essential prerequisite for good operational management and a reliable supply of energy. ITs are precise measuring instruments that have to satisfy the most stringent demands in terms of operating range and insulation. Incorrect operation, the use of defective ITs, or the failure of an installed IT can have far-reaching financial, as well as technical, consequences [1]. In addition to these op-

teristic behavior of current transformers is their (extreme) quasi-short circuit operation with a low-impedance burden.

In such a case, the ideally transformed primary current will not be present in the secondary side of the current transformer. Instead, it will be reduced by an amount proportional to the magnetizing current (error compensation is possible by adjusting the number of turns). As the operating burden increases, so does the induction in the core and hence the magnetizing current, which, with the aforementioned simplifications, is the only possible cause of the transformer error. Changes to operational parameters in terms of current and burden therefore affect the ratio and phase accuracy of current transformers.

The current measurement deviation is calculated according to equation 1 (related to Fig. 1). The phase error is the difference in angle between the primary and secondary current vector and will be negative when the secondary current vector is lagging [2].

$$\varepsilon_I = (K_n I_b - I_{1P})/I_{1P} \cdot 100\ \% \qquad (1)$$

The transformer equivalent circuit can also be applied to voltage transformers.

However, the primary resistance and leakage reactance cannot be ignored [3]. Voltage transformers are operated under quasi no-load conditions and are therefore connected to an extremely high-impedance burden.

Voltage drops occur on the winding resistors R_1'' and R_2 due to the burden current i_b and the excitation current i_0, causing the ideally transformed input voltage to differ from the output voltage – and resulting in an error. The leakage flux (a quantity that is geometry dependent) also causes a lower voltage to be induced on the secondary terminals than the voltage that has been induced on the primary side as corresponding flux to the primary voltage ($\Psi = U_{1HV}/(2\pi f)$). The associated additional "losses" are modeled in the equivalent circuit with a reactance that is split between the primary and secondary sides.

The leakage and winding capacitances shown in Figure 2 can be ignored in order to simplify the description of the ratio accuracy at operating frequency. As the voltage rises, however, the primary capacitance generates an additional capacitive current due to the design of the primary winding. This capacitive current can influ-

erational aspects, manufacturers endeavor to produce high-quality equipment at a reasonable cost. Carrying out the correct tests during the production process will not only save time, but also improve the quality of the final product [1].

2. Fundamentals

Current and voltage transformers are normally single-phase transformers, which, despite their differences in design, can essentially be described using the familiar transformer equivalent circuit diagram.

2.1. Current and voltage transformers

In the case of a current transformer, typically the primary elements can be ignored when modeling the equivalent circuit. In general, the secondary stray inductivity can be ignored without introducing any major calculation errors if the closed core design is symmetrical in terms of winding. At the nominal frequency of 50/60 Hz, the leakage capacitances can also be ignored. A charac-
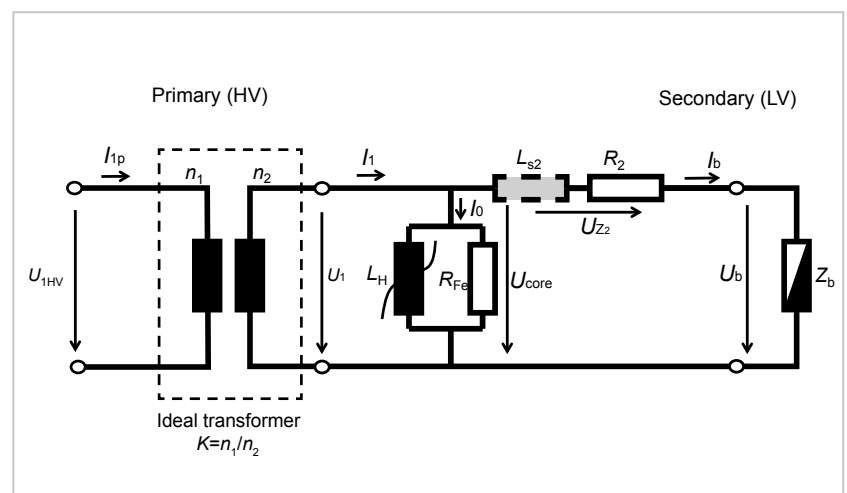

Figure 1. Simplified, qualitative equivalent circuit for current transformers, referred to secondary side

Although the cost of ITs is relatively low, their correct and uninterrupted operation is an essential prerequisite for good operational management and a reliable supply of energy
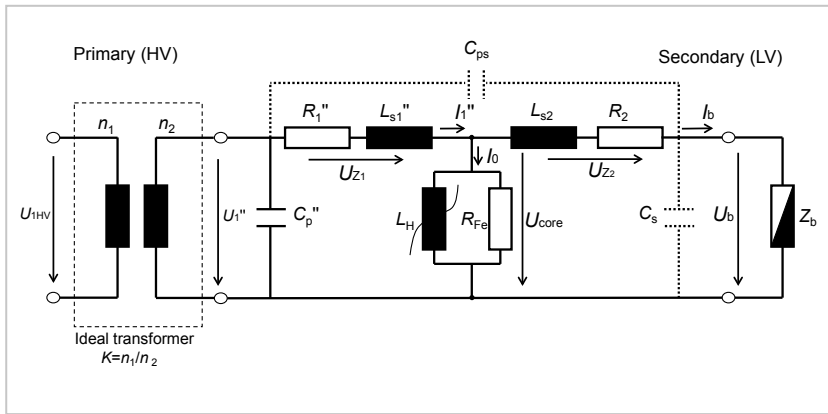
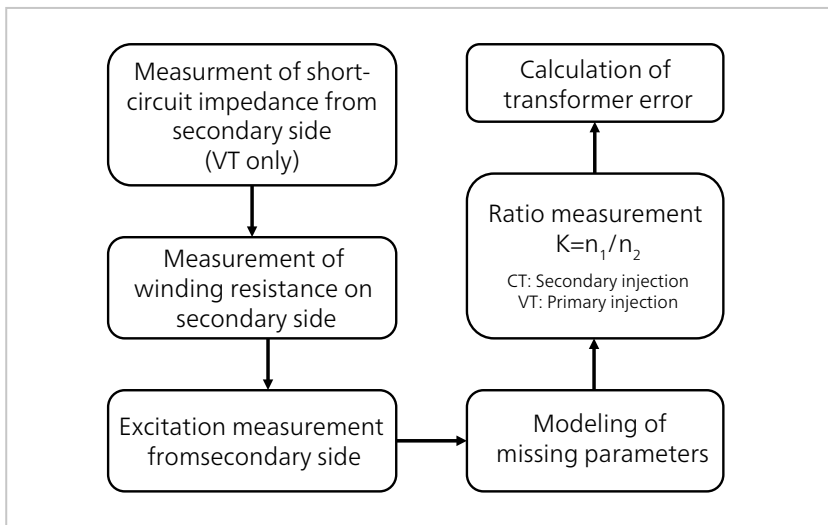Figure 2. Simplified, qualitative equivalent circuit for voltage transformers, referred to secondary side

Figure 3. Block diagram for model-based accuracy verification of current and voltage transformers

Model-based accuracy verification enables all the relevant transformer parameters to be determined without applying a nominal current or nominal voltage

ence the transformer error (especially the phase-angle error) [4].

The voltage measurement deviation is calculated according to equation 2 (connected to Fig. 2). The phase error is the

difference in angle between the primary and secondary voltage and will be negative when the secondary voltage vector is lagging [5].

$$\varepsilon_U = (K_n \cdot U_b - U_{1HV})/U_{1HV} \cdot 100\,\% \qquad (2)$$

2.2. Model-based transformer testing

Model-based accuracy tests have been developed [6, 7] based on the equivalent circuits shown in section 2.1 and the opportunity they provide to calculate the accuracy of the transformer (for example, [3]). Carrying out various measurements of the equivalent circuit parameters with small signals compared with the nominal quantities allows the calculation of the non-linear dependent accuracy of current (CT) and voltage transformers (VT), which depends on the voltage, current and burden, Fig. 3.

Using this approach, the measurements of the excitation properties take place, regardless of the device being examined, from the secondary side using the single-winding method (compare [6] for VTs). The voltage drop across the secondary elements is taken into account when calculating the induction. The input voltage is sinusoidal. Any non-linear induction caused by the non-linear excitation current is ignored.

Model-based accuracy verification enables all the relevant transformer parameters to be determined without applying a nominal current or nominal voltage. The model-based verification also permits all the parameters specified in the standard to be calculated as shown in Table 1 (the table may not be fully comprehensive).

3. Tests and diagnostics carried out by the manufacturer

3.1. Preliminary testing of the transformer

Preliminary testing (testing before the IT is completely manufactured) is unavoidable if an efficient and high-quality manufacturing process is the aim. In particular, preliminary testing ensures that any errors that occur during critical production phases are not carried over the whole manufacturing process into the final type test or routine test (compare [1]). The model-based approach enables adherence to the specifications to be checked at various stages of the production process. This test goes beyond the ratio testing that is normally carried out. The transformer can be tested using low-level test signals, even if they do not yet fulfill all the requirements regarding insulation.

Table 1. Overview of transformer parameters

Type of transformer	Application	Parameters
CT	Metering	ε_I, δ_I, FS
	Protection	ε_I, δ_I, ALF, K_r, T_s, R_{CT}, E_K, I_e, ε_t, K_{td}, K_{ssc}
VT	Metering	ε_U, δ_U
	Protection	ε_U, δ_U

The following critical process steps can be identified, for example: selection of the right type of core material for the application in question (testing after winding or stacking of the core); the winding process (testing after applying the primary and/or secondary winding); and casting or installation in the housing (testing before final installation). If, for example, corrections can still be made before casting, then any transformer that has already been casted will have to be produced again if it fails to meet the specified (limit) values.

Figure 4 shows an example of the process involved in the manufacture of medium-voltage current and voltage transformers.

Testing of the magnetic properties can be carried out at point A. As there is no winding that can be used for the measurement at this point, a temporary winding must be used. The connecting cables required to carry out a four-wire measurement using the single-winding method are connected via a "flexible coil" in the form of a cable. If the core dimensions are known, the magnetic parameters can be determined. The relative permeability μ_r, the saturation inductance, and the losses are of particular interest at this stage.

An insulation test can be carried out at points B and C after producing the windings for a voltage transformer; this will highlight any damage to the winding wire.

Once the core-and-coil assembly is complete (in the case of a voltage transformer) or the secondary winding applied (current transformer), a ratio measurement and the first model-based testing can take place. It will still be possible to do corrections at this stage if certain parameters are not met. The ratio measurement or model-based test can then be repeated after the correction (E). After installation in the housing and casting, repeating the previous tests will establish what (mechanical) effect the casting has had on the accuracy of the transformer. A dielectric test can also be carried out at this point to assess the quality of the potting and/or insulation, see Table 4.

3.2. Model-based testing as a development tool

Current and voltage transformers are usually individually configured and/or manufactured according to the customer's specifications. The electrical calculation
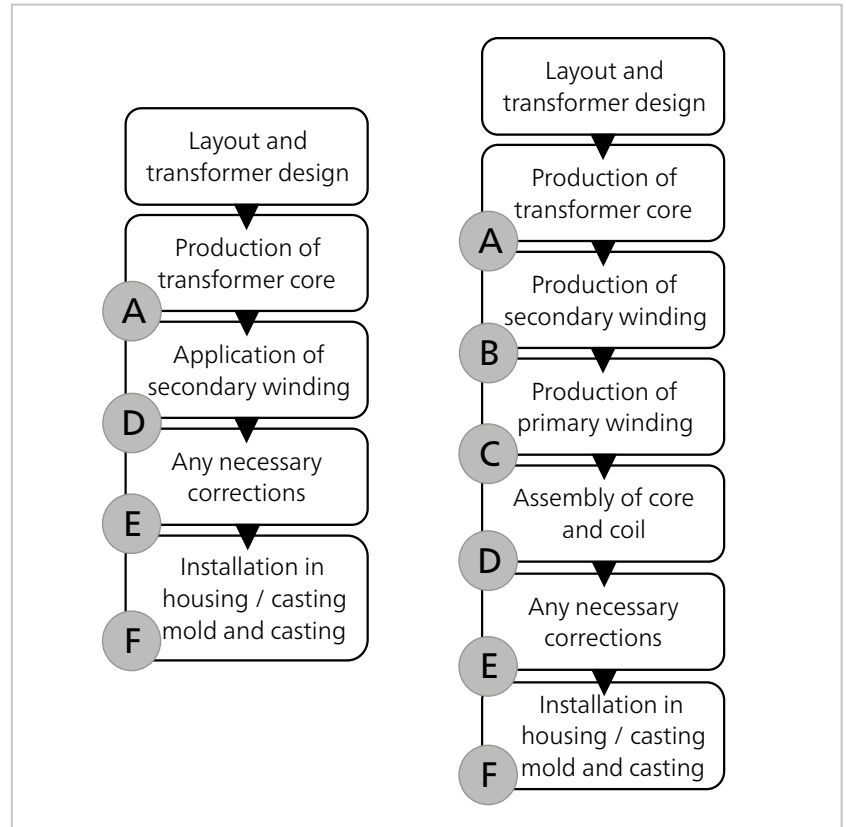
Figure 4. Critical production steps for medium-voltage current (left) and voltage (right) transformers
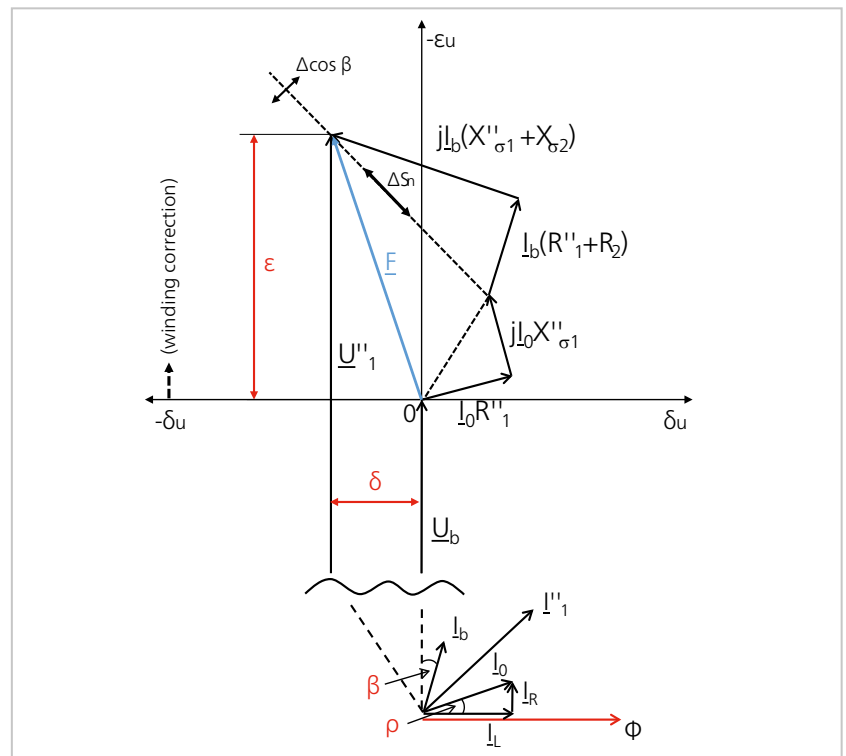

Figure 5. Voltage transformer phasor diagram [6]

Table 2. Results of ratio measurement with primary injection

Primary current I_p in A	Secondary current I_s in A	Ratio K	Phase displacement δ in °
100.00	0.05004	1998.4:1	0.22
200.00	0.10007	1998.6:1	0.21
400.00	0.2	2000.0:1	0.23
600.00	0.30011	1999.2:1	0.2
799.99	0.40028	1998.6:1	0.18

Table 3. Results of ratio measurement with primary injection

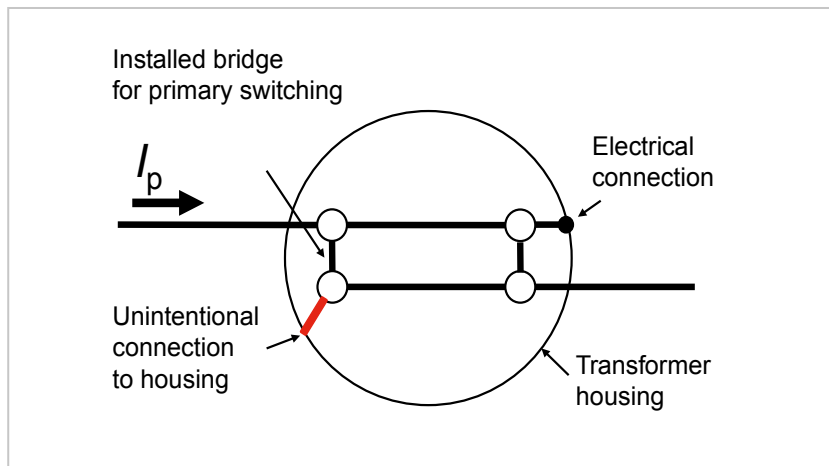| Ratio K	Phase error δ_l in min	Ratio error ε_l in %	Polarity
2045.5:1	0.543	-2.2627	OK

Figure 6. Wiring diagram showing current transformer with unintended housing contact (red)
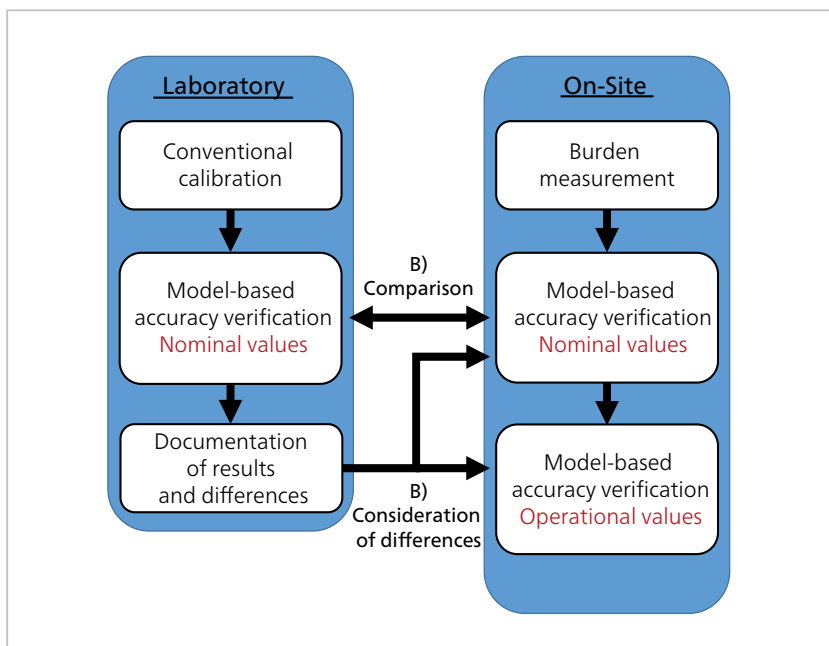

Figure 7. Procedure for on-site calibration of current and voltage transformers using model-based calibration

(nominal operation and transient behavior) of the transformer employs a range of design criteria [1, 3, 4] based on the equivalent circuit and the Möllinger and Gewecke phasor diagram, as exemplified for the voltage transformer shown in Figure 5.

The dependency between the fault vector $\underline{F}$ and the individual parameters in the equivalent circuit can best be illustrated using a phasor diagram.

As the accuracy of the transformer depends not just on the properties of the materials used for the windings and core but also on the geometry (leakage reactance X_σ), it can be affected by the choice of material, the design, and the production technology. The use of model-based testing provides an opportunity to compare the previously calculated variables with the measured variables taken from the prototype (design verification), as well as to determine various other parameters, such as the distribution of the leakage inductance.

As well as the (distribution of the) leakage inductance L_σ, the excitation curve (U_{core}, I_0) is also of interest, as this determines the voltage-dependent no-load error and plays an important role regarding ferro-resonance.

4. On-site testing of current and voltage transformers

4.1. Acceptance and commissioning tests

Checking the transformer ratio and the polarity is part of the acceptance and commissioning test and enables any transport damage or installation errors to be detected. The testing of current transformers, for example, involves injecting a primary current, which is measured on the secondary side. The following example demonstrates

that this test is unable to pick up certain installation errors, with the result that failure may occur further down the line. Additional testing using the model-based approach as set out in section 2.2 is therefore recommended. Testing of the transformer ratio of a high-voltage current transformer (2000:1, class 0.2S as per IEC 61869, 5VA, FS10) with a primary current injection produces the results shown in Table 2.

As the results show, the ratio K tends to be lower than the nominal value of 2000:1. Due to the low values, the ratio also depends on the accuracy of the current measurement I_s. Looking at the results, it could be assumed that the test was "passed", as the result is close to the nominal value (it would be a good idea to check against reference values). Carrying out an additional model-based test for nominal operation with a primary current of 2000 A produces the results shown in Table 3.

The accuracy following the model-based test is not within the limits of +/- 0.2 % as specified in the IEC 61869 standard [5]. The ratio value is also higher than that obtained when testing with a primary current. The polarity and phase error are acceptable.

The accuracy of the transformer can be affected by the choice of material, the design, and the production technology ''

The model-based testing determines the parameters and performs the ratio measurement from the secondary side using the voltage method ($K=U_1/U_{1HV}$, compare Fig. 1). This helps detect a primary short circuit, as in this example. In the case of the secondary voltage method, the core voltage $U_{core}=U_1$ is calculated using the secondary voltage injected, and the induced voltage U_{1HV} is measured on the primary winding.

The differences in this example can be attributed to a short circuit of the primary conductor. The housing on the head of the current transformer is, under normal circumstances, electrically connected at one end to the primary conductor (same potential), compare Fig. 6. In this example, the housing is wrongly connected to the primary conductor at both ends, resulting in a (partial) short circuit of the primary current.

The unintended connection in the above example has a sufficiently high impedance to prevent it being noticed when the primary current is injected. With model-based testing, on the other hand, the short circuit on the primary side makes the ratio larger, as the measured primary voltage U_{1HV} will be lower ($K=U_1/U_{1HV}$).

4.2. Calibrating current and voltage transformers

Current and voltage transformers are generally only calibrated as part of a routine testing procedure once they have been manufactured. There is nothing in any of the international standards that requires subsequent calibration on site or for the calibration to be repeated after the transformer has been in operation for a specified period. However, such a requirement is set out in some local and internal company regulations. On-site calibration of the transformer

Table 4. Sample overview of transformer diagnosis

Testing procedure	Detectable faults/parameters
Ratio measurement	Shorted windings, poor connections, primary wiring (CT), open connections, incorrect wiring of built-in devices (for example, in circuit breakers, transformer bushings)
Accuracy verification, conventional or model-based	See above + influence of operational parameters (current, voltage, burden), loose laminations (in the case of HV transformers), displacement of primary winding (in HV transformers), short circuit of primary conductor (CT, model-based only)
Overall model-based transformer testing	Transformer parameters (for example, ε, δ, ALF, FS, RCT, L_σ, ...)
	Transient parameters (for example, Ts, Ktd, etc.)
Measurement of excitation curve	Loose laminations (in the case of HV transformers), operational inductance due to susceptibility to ferro-resonance, protection transformer parameters, short circuits or shorted windings, distortion of air gap
Measurement of core properties	Remanence (current transformers), permeability, wattage losses, saturation inductance
Polarity measurement	Winding faults, connection errors
Partial discharge measurement	Internal faults in insulation, cavities, cracks, floating potential
Dissipation/power factor and capacitance measurement	Condition of insulation (conductivity and polarization losses), tap contact (CT)
Dielectric response measurement (FDS, PDC) (μHz-kHz)	Humidity (oil-paper insulated transformers), aging of insulation, contamination
Voltage withstand test	Insulation capacity, short circuits
Oil analysis	Partial discharge activity, sparking (thermal), moisture, electrical resistance, aging condition of oil
Insulation resistance measurement	Condition of insulation

On-site calibration of the transformer is sometimes advisable, as the changed load conditions or transport damage may have affected its accuracy

is sometimes advisable, considering that in the period since the original calibration in the lab the topology of the transformer (for example, in the case of separable current transformers) or load conditions may have changed, transport damage may have occurred, or other operational factors might have affected its accuracy (for example, aging of capacitive stack of CVTs).

Calibration in this context means checking the accuracy (ratio error and phase error) using reference values; error thresholds must not be violated. A conventional calibration in an accredited laboratory involves measuring the difference between a standard transformer and the test object.

As conventional calibration requires a current or voltage source in excess of the nominal values, together with the physical burden and a comparator for measuring the difference, on-site testing demands extensive technical and financial resources (refer to [8] for more details). Model-based testing as described in section 2.2 compensates for these drawbacks while providing additional benefits in terms of time, safety, and extra information, compare Table 1.

To perform a traceable calibration, a range of steps must be carried out [9], as illustrated in Figure 7. A conventional calibration of the test object is carried out in an accredited laboratory. This is followed by a model-based test without modifying the transformer topology. The results and any differences between the two measurements are documented.

Finally, a measurement of the operating burden and two model-based tests using the nominal burden and the measured operating burden are then carried out on site.

If the initial, direct comparison between the conventional calibration with a standard transformer and a comparator in the laboratory is not available, the accuracy test can also be carried out (without traceability) using the typical accuracies of the model-based test.

5. Overview of transformer diagnosis

The testing and diagnostics methods listed and commented on in Table 4 are those the author believes to be the most useful in respect of detectable faults and parameters. The processes shown are based on the diagnosis of completed transformers.

These testing methods enable an assessment of the transformer to be carried out on an application-by-application basis. There is no all-embracing "correct procedure" in terms of the application, but the appropriate test for the desired purpose should be performed at a suitable point. Direct processes (for example, oil analysis) come with a significant risk and are not recommended for ITs, as often they do not tell us very much (subsequent measurements necessary) and necessitate manual intervention in the system [1].

Conclusion

This article examines and discusses the importance of testing and diagnostic methods applied to medium- and high-voltage instrument transformers throughout their complete life cycle, illustrating them with a number of examples.

Acknowledgement

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