Automated test systems for distribution transformers – Part I

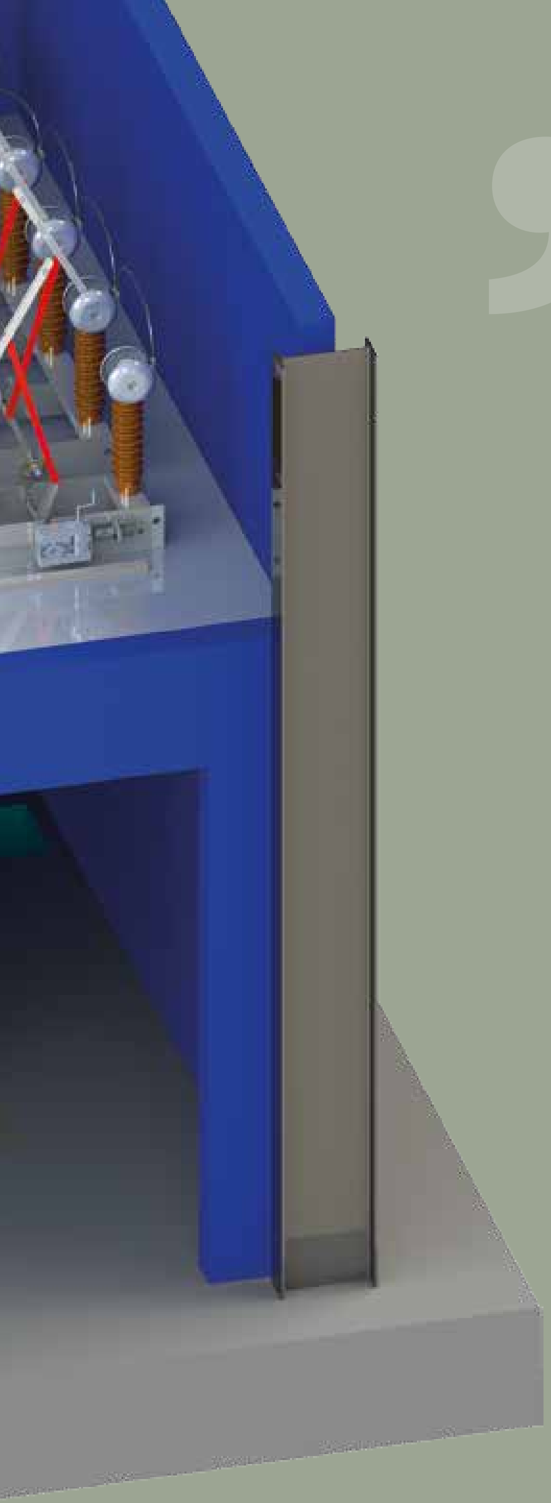
Test requirements and principal structure of the test system

ABSTRACT

Distribution transformers are used worldwide and in very large quantities as a link between regional medium-voltage networks and local low-voltage distribution systems. To ensure quality, the required electrical characteristics must be demonstrated through extensive testing procedures on each distribution transformer in the production. This paper gives an overview of the equipment for automated testing of distribution transformers. There are also various options presented for a significant reduction of the required test time which can be achieved by optimizing the interaction of automatic switching devices, intelligent system control and largely intuitively designed test sequences.

KEYWORDS

automated testing, distribution transformer, transformer testing, high-voltage test equipment, factory testing



> **Since every single distribution transformer must undergo intensive electrical testing before it can be delivered to the customer, the test system used must also be able to perform tests within the shortest time period possible, so that the production process is not slowed down**

1. Introduction

The distribution of electrical energy is divided into multiple interconnected power grids, which are operated at different voltage levels. These include, as for example in the European Union, an extra-high-voltage grid (> 110 kV), a high-voltage grid (110 kV), a medium-voltage grid (< 36 kV) and local low-voltage grids (400 V). The transmission of electrical energy and voltage matching between different voltage levels requires the use of transformers.

Distribution transformers, which are connected to medium-voltage grids, are used for general low-voltage power supply of buildings and industrial users. They are also used in cases where electrical energy that is generated in small power stations, such as solar farms or wind farms, is fed directly into the medium-voltage grid.

In contrast to large transformers, distribution transformers are produced and used worldwide on a much larger scale. From an economic point of view, the demands in terms of production and electrical testing differ greatly among these transformer types, since the time required for each production step represents a certain cost factor. Manufacturers thus strive to reduce the individual times to a technically feasible minimum. Since every single distribution transformer must undergo intensive electrical testing before it can be delivered to the customer, the test system used must also be able to perform tests within the shortest possible period of time, so that the production process is not slowed down.

2. Factory testing of distribution transformers

Together with the quality assurance processes, the routine tests that have to be conducted on each distribution transformer after production serve to demonstrate that the customers' requirements in terms of the electrical parameters have actually been satisfied. Additional testing is conducted in the form of type tests before a newly developed transformer type can move to the series production stage. Such type tests are performed once on a prototype that is representative of the corresponding production series to demonstrate that it has all of the required properties.

Various national and international standards provide detailed recommendations for the performance of routine tests and type tests, including, for example, VDE, IEC and IEEE [1], [2], [3].

The most important electrical tests for distribution transformers can be divided into three main groups:

1. Measurements of operating characteristics
2. Load performance tests
3. Proof of the dielectric strength of the insulation between the windings and windings to ground

2.1 Measurements of operating characteristics

According to the standard IEC 60076-3 [2], the first group of tests includes measurements of general characteristics of the transformer, such as transformation ratio (turn ratio), vector group, DC winding resistance and insulation resistance. The measurements are conducted using largely standardised test equipment, which uses only low electric power for testing. In contrast, the measurement of no-load current and no-load loss (iron loss) requires higher test power. It is generally performed by supplying a test voltage at the nominal voltage level to the low-voltage side of the transformer. Due to the low currents involved in this test, no significant losses occur in the windings, so that only the losses that are actually generated in the magnetic circuit are measured.

2.2 Load performance tests

The second group, load performance tests, includes the measurement of load losses and the *heat run test* conducted during type testing to determine the temperature rise at nominal load [2]. Transformer tests at nominal current are generally performed in short-circuit mode. For this, the low-voltage side of the transformer under test is shorted, while the test voltage, set to a level that ensures the nominal current is reached, is supplied to the high-voltage side. With this test arrangement, the required apparent power is determined by the short-circuit voltage, which typically lies in a range between 4 and 6 per cent.

Customers place great demands on transformer manufacturers as regards loss measuring uncertainty because the costs for the load loss of distribution transformers during their entire service life represent a major economic factor

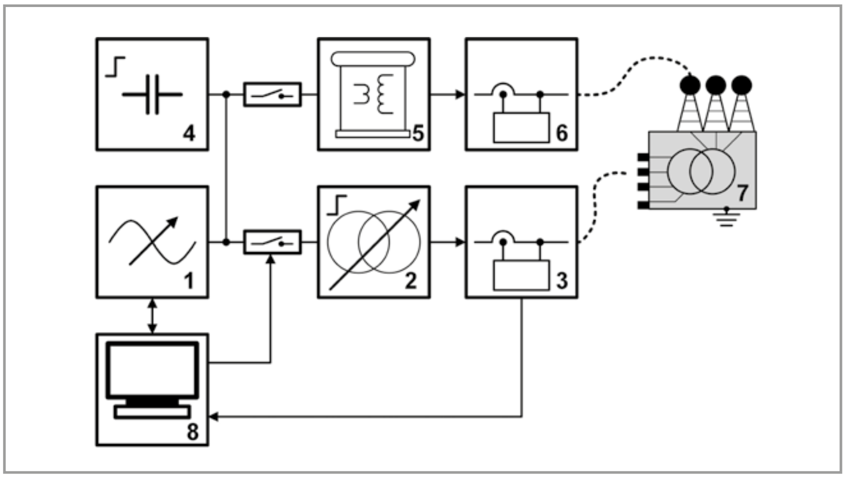


Figure 1. Simplified set-up for testing distribution transformers

For large distribution transformers with a nominal rating of 5,000 kVA and 6 per cent short-circuit voltage, however, the apparent power for testing can still be as high as 300 kVA, which must be supplied by the test system.

Due to the low test voltages and the resulting low excitation of the iron core in such test configuration, it is almost exclusively the losses in the windings that are measured in the *short-circuit test*. Since the losses in the form of active power only account for a small portion of the entire apparent power for testing, measuring the latter requires a highly precise power measuring device with very low phase error between current and voltage measuring channel. Since the costs for the load loss of distribution transformers during their entire service life represent a major economic factor, customers place great demands on transformer manufacturers as regards measuring uncertainty.

2.3. Proof of the dielectric strength

The third group of electrical tests serves to demonstrate the insulating properties between the windings and between windings and parts connected to earth potential [2]. This is demonstrated by applying higher test voltages, in distribution transformers typically up to twice the nominal voltage. The dielectric strength between the winding layers of one winding and between neighbouring individual wires is tested by supplying an AC test voltage ranging between 800 V (for a rated voltage of 400 V) and up to 2,000 V (for a rated voltage of 1,000 V) to the low-voltage side of the transformer under test, which is called the *induced voltage test*. The high voltage in the high-voltage winding, which is needed for the insulation test, is generated by the transformer under test itself. Even smallest flaws in the insulation, such as air pockets or conductive foreign particles, can be identified before the insulation actually breaks down, because the occurrence of partial discharges is detected.

Partial discharges inside the transformer lead to multiple, very short high-frequency current pulses in the supply lines that show a characteristic pattern relative to the phasing of the test voltage. These current pulses are separated from the test voltage with the help of external coupling capacitors and analysed using special Partial Discharge (PD) measuring equipment. To be able to reliably detect the current pulses even with low-intensity partial discharges, the test voltage must only have a very low proportion of high-frequency interference. This is achieved by filtering the test voltage via special PD low-pass filters with high attenuation and by means of the optimised earthing concept of the test system.

To avoid magnetic saturation of the laminated core during the *induced voltage test*, the frequency of the supplied test voltage must be increased at least by the ratio of test voltage to nominal voltage. Mechanically coupled motor-generator units were formerly used for this, and were able to provide adjustable voltages with correspondingly high frequencies. In modern test systems, this is achieved through static frequency converters, which allow voltage conversion without the need for moving parts.

The insulation between low- and high-voltage windings, and between the windings and parts connected to earth potential, are tested by supplying an externally generated single-phase test voltage to the particular winding. This test requires a high AC test voltage up to 70 kV for a rated voltage of 36 kV, which is provided by a separate high-voltage transformer.

3. Principal structure of the test system

A high-performance AC power source capable of delivering a variable voltage output with adjustable frequency and the apparent power needed for the test is required in order to carry out routine tests on distribution transformers. A frequency that differs from that of the mains voltage is particularly important for the *induced voltage test*, where the frequency is increased up to twice the nominal frequency of the transformer under test, sometimes even more. This adjustment option is further needed when testing distribution transformers that are exported to regions where the frequency of the local power grids differs from standard grids (50/60 Hz). The voltage range that is required for performance of the individual tests lies roughly between the nominal voltage of the transformer's low-voltage side for the *no-load test* and up to 5 kV for the *load loss test* and *heat run test*, where the voltage is supplied to the high-voltage side.

A possible set-up for testing distribution transformers is shown in Fig. 1. With this arrangement it is not only possible to conduct the standard tests described above, but also to perform the *heat run test* as part of the type testing procedure, provided all parts of the system are adequately dimensioned.

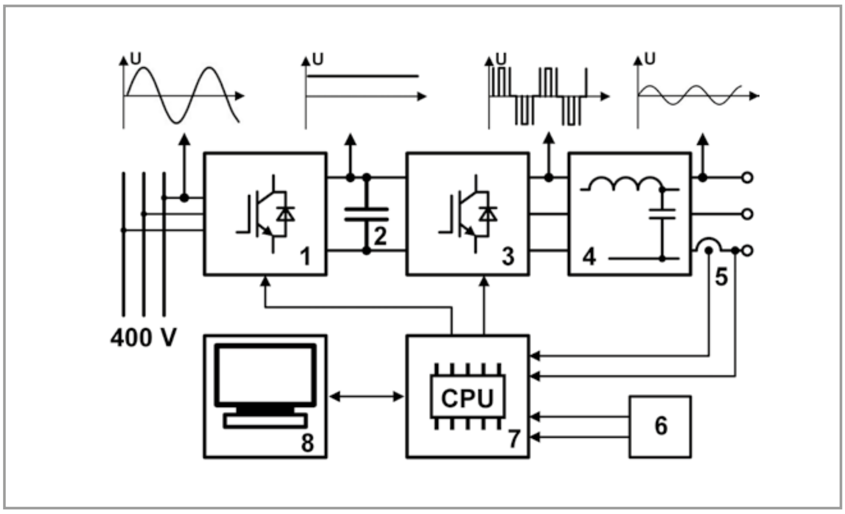


Figure 2. Static frequency converter

> **With the advanced test system it is possible to conduct standard tests and the heat run test, provided that all parts of the system are adequately dimensioned**

A static frequency converter (1), in conjunction with internal filters, serves as the central source of the test system. It provides three-phase AC voltage whose amplitude and frequency are adjustable within wide ranges.

To exploit as much of the frequency converter's capability as possible, a multistage step-up transformer (2) is used to generate the required test voltage. Switching between the individual stages is performed by motor-driven medium-voltage contactors while the step-up transformer is de-energised.

To reduce the strain on the frequency converter, the bulk of the inductive reactive power required for the tests is provided through capacitive compensation (4). Thanks to this compensation, the static frequency converter only has to cover the remaining, non-compensated reactive power and the heat losses that occur in the test system and transformer under test (7). This arrangement means that frequency converters with relatively low nominal power can be used, which helps reduce the investment costs for the test system.

The voltage on the transformer under test (7), the test current and, most of all, the active power that is converted in the transformer under test are measured using a special power loss measuring system (3). This system comprises three voltage sensors and three current sensors, as well as a central signal processing unit for processing and transferring the measured values. Due to the very low power factor of the transformer under test, the measuring accuracy of the power loss measurement strongly depends on the precision with which the phase angle between current and voltage is determined. To make the measurement as accurate as possible, the amplitude errors and angle errors of the individual voltage and current sensors, as well as of the corresponding signal processing units, are measured separately and stored in the device. During the measurements, these stored data are used for permanent correction of the values measured by the individual sensors, so that the power loss is determined with extremely high accuracy.

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An additional high-voltage transformer (5) is used for the tests where the voltage is supplied to the high-voltage side of the distribution transformer under test. It is also fed through the static frequency converter and provides a test voltage of up to 70–100 kV. The exact voltage and test current are determined by a separate measuring system (6). Since tests of this kind do not involve power measurement, the accuracy demands on this measuring system are somewhat lower. The *insulation test*, which is carried out by applying a voltage to the low-voltage side, is typically conducted at considerably lower voltage, which is provided by a separate winding of the step-up transformer (2). In this case, the voltage level and test current are determined by the power loss measuring system (3).

4. Using static frequency converters in the test system

Static frequency converters have been used successfully for many years in test systems for transformer testing, so that they have now widely ousted the motor-generator units that were used before. The frequency converters boast a number of advantages, including lower maintenance costs and, in particular, extensive and very fast control and protection features. Another great benefit is the possibility to adjust frequency and amplitude independently and continuously over a wide range. Furthermore, it is also possible to actively correct any distortion of the voltage curve caused by the non-linear current draw of the units under test.

The short response time of the frequency converter of just a few microseconds also allows the arc energy transferred at the point of breakdown to be minimised if the insulation of the transformer under test fails.

Fig. 2 schematically shows the design of a static frequency converter. The simplified voltage curves of the individual components

Static frequency converters have now widely ousted the motor-generator units that were used before due to lower maintenance costs, extensive and very fast control and protection features, the possibility to adjust frequency and amplitude independently and continuously over a wide range, etc.

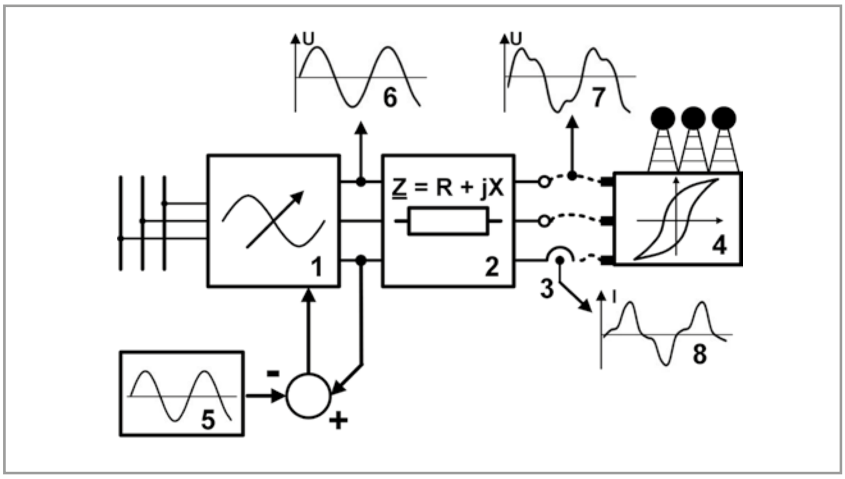

Figure 3. Voltage distortion without direct high-voltage control

are shown in the upper part of the diagram.

A controlled mains rectifier (1) is supplied from the three-phase low-voltage grid. It provides a controlled DC voltage, which is smoothed by DC-link capacitors (2). The setpoint values for current, voltage and controller limits are provided by the system controller (8) of the test system. On the basis of the existing setpoints and actual values, the internal controller of the frequency converter (7) uses modulation methods to calculate a high-frequency pulse pattern, which then controls the individual semiconductor switches of the three phases of the inverter (3). A multi-stage low-pass filter (4) transforms the sequence of high-frequency voltage pulses of the inverter into a sinusoidal voltage that only has very small high-frequency harmonic components. In the simplest case, the voltage is measured directly at the output of the low-pass filter (5) and transmitted to the central controller of the frequency converter. If the measured amplitude, phasing or voltage curve deviates from the given setpoint values, the internal controller will modify the pulse pattern in such a way that the deviations are corrected. As an alternative way to improve the control quality, it is also possible to directly feedback the voltage from the transformer under test (6).

It is of particular importance when testing transformers that the output voltage does not contain any DC voltage portions. They would lead to a strong magnetic bias of the iron core and hence to saturation effects with very high, asymmetric no-load currents. For an application in test systems, the controller of the frequency converter needs special control circuitry that ensures the provision of an absolutely DC-free output voltage.

During *no-load tests* of transformers, the current draw may nonetheless show some distortion. This is the case in particular where the laminated core is overly excited, i.e. when it is operated near the magnetic saturation point. This behaviour is shown in a simplified diagram in Fig. 3. The test current (8) that flows through the non-linear transformer under test (4) shows noticeable deviations from the sinusoidal shape. The controller of the frequency converter (1) adapts the output voltage directly at the inverter and ensures a perfect sinusoidal voltage curve (6) there. However, an additional step-up transformer with a certain impedance Z (2) is located between the frequency converter and transformer under test. The voltage drop over this impedance cannot be compensated for in this type of circuit, as a result of which the test voltage at the output of the test system is distorted (7).

To minimise this distortion, a method known as direct high-voltage control is

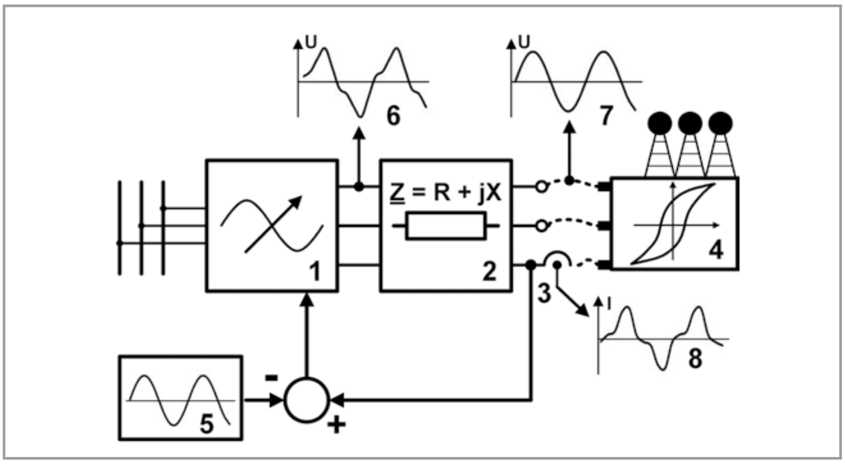

Figure 4. Direct high-voltage control

It is of particular importance when testing transformers that the output voltage does not contain any DC voltage component in order to avoid saturation effects with very high, asymmetric no-load currents

used, which is shown in a simplified diagram in Fig. 4.

Here, the test voltage (3) is directly used as the actual value for the internal controller of the frequency converter (1). Through a comparison with the reference variable (5), the frequency converter generates a voltage curve (6) that compensates for the voltage drop over the impedance Z of the step-up transformer. In this way, the test voltage at the output of the test system shows only very little distortion (7) despite the non-linear current. In addition to the above-described compensation of the distortion in the curve shape, direct high-voltage control also allows the phase angle of the three phases to be corrected if the load on the transformer under test is unbalanced.

Furthermore, this control method permits the test voltage to be adjusted with high precision and irrespectively of the actual load.

In the second part of this paper, features of the test system will be presented and discussed in more detail.

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