Automated test systems for distribution transformers DiTAS

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Distribution transformers are used on a very large scale world-wide to connect regional medium voltage networks to local low-voltage networks. For quality assurance purposes, extensive test procedures are performed during production to ensure compliance with the required electric properties. This paper outlines the principle of operation of the testing and measuring technology required for the automated testing of distribution transformers. It also presents various ways of optimizing the interaction between automatic switch-over devices, intelligent system control and mainly intuitively-designed test procedures to reduce testing time.

The distribution of electrical energy is divided into multiple interconnected power grids, which are operated at different voltage levels. These include 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 the different voltage levels requires the use of transformers.

Distribution transformers are used for general low-voltage power supply of buildings and industrial users from the medium-voltage grid. 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 world-wide 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 is 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.

Shop-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 (IEC 60076, VDE 0532 Part 3, DIN EN 60076-3).

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

- general operating parameters
- load performance
- insulation test.

The first group of tests includes measurements of general characteristics of the transformer, such as transformation ratio, vector group, DC winding resistance and insulation resistance. The measurements are conducted using largely standardized 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.

The second group – load performance tests – includes the measurement of load losses and the "heat run" conducted during type testing to determine the temperature rise at nominal load.

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. On the high-voltage side, a test voltage is supplied that is set to a level that ensures the nominal current is reached. With this test arrangement, the required apparent power is then only a fraction of the nominal power of the unit under test, and it is determined mainly by the short-circuit voltage, which typically lies in a range of between 4 and 8 %. With large distribution transformers, however, the apparent power for testing can still be as high as 400 kVA, which must be supplied by the test system.

Due to the low test voltages, 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 power loss of distribution transformers during their entire service life are a major economic factor, customers place great demands on transformer manufacturers as regards measuring uncertainty.

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

Partial discharges (PD) inside the transformer lead to many very short high-frequency current pulses in the supply lines that show a characteristic pattern relative to the phasing of the test voltage. External coupling capacitors separate these current pulses from the test voltage which are then analyzed using special partial discharge measuring equipment. To be able to reliably detect the current pulses even with low-intensity partial discharges, the test voltage must only comprise a very low proportion of high-frequency interference. This is achieved by filtering the test voltage via PD low-pass filters with high attenuation and by means of the optimized 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, which were able to provide adjustable voltages with correspondingly high frequencies. In modern test systems, static frequency converters are used 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 test voltage in the range from 70 kV to 100 kV, which is provided by a separate high-voltage transformer.

Set-up 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 *diagram 1*. With this arrangement it is not only possible to conduct the standard tests described above, but also the heat run as part of the type testing procedure, provided 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 multi-stage 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-energized.

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 unit 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.

A power loss measuring system (3) measures the voltage applied to the unit under test (7), the test current and, most importantly, the active power converted in the unit under test. 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 low power factor of the unit 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 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. 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 measure power, the accuracy demands on this measuring system are somewhat lower.

An applied voltage test at lower voltages, which are provided by a separate winding of the step-up transformer (2), is typically used to test the insulation of the low-voltage side. In this case, the voltage level and test current are determined by the power loss measuring system (3).

Frequency converters in test systems

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 for 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 milliseconds also allows the arc energy transferred at the point of breakdown to be minimized if the insulation of the unit under test fails.

Diagram 2 shows the schematic design of a static frequency converter. The simplified voltage curves of the individual components 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 link-circuit capacitors (2). The setpoint values for current, voltage and controller limits are determined by the test system controller (8).

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 modifies the pulse pattern to correct the deviations. As an alternative way to improve the control quality, it is also possible to directly feed back the voltage from the unit under test to the inverter (6).

When testing transformers, it is also important 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 control circuitry that ensures the provision of an absolutely DC-free output voltage.

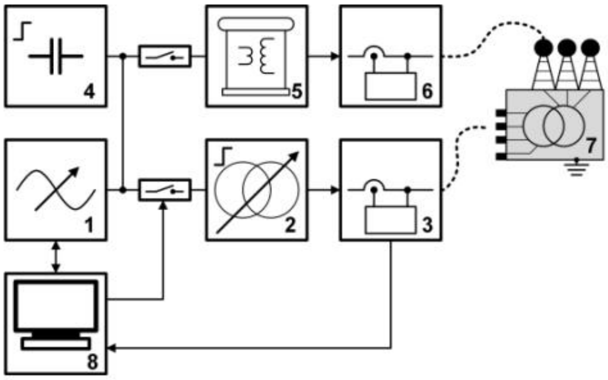

Diagram 1. Set-up for testing the distribution transformers

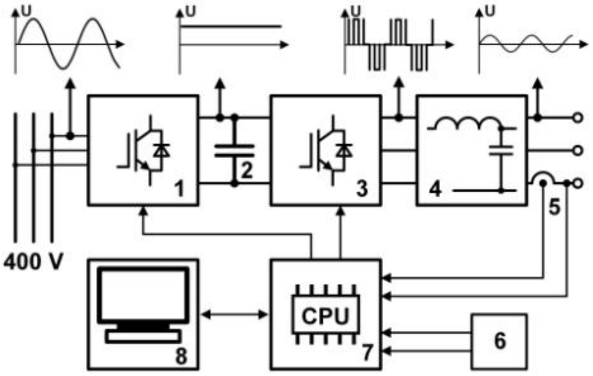

Diagram 2. Schematic design of a static frequency converter

During no-load tests of transformers, the current draw may nonetheless show some bias. 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 behavior is illustrated in a simplified manner in *diagram 3*. The test current (8) that flows through the non-linear unit under test (4) deviates significantly from the sinusoidal form. The controller of the frequency converter (1) accordingly adapts the output voltage directly at the inverter and ensures a perfect sinusoidal voltage curve (6) there.

An additional step-up transformer with impedance Z (2) is located between the frequency converter and the unit 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 (7) at the output of the test system is distorted. To minimize this distortion, a method known as direct high-voltage control is used, which is shown in a simplified manner in *diagram 4*.

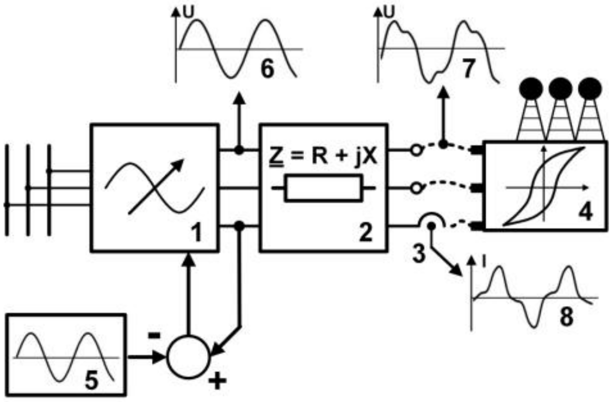

Diagram 3. Current distortion during operation in magnetic saturation

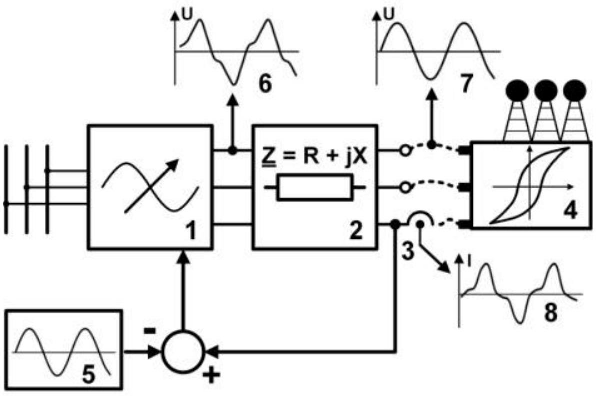

Diagram 4. Distortion reduction by means of direct high-voltage control

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 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 unit under test is unbalanced. Furthermore, this control method permits precise adjustment of the test voltage irrespective of the actual load.

Time needed for routine tests

The time needed to conduct a full routine test of a distribution transformer mainly comprises the following elements:

- total time needed for the individual tests
- system set-up time
- time needed for the reconfiguration of the test system and reconnection of the unit under test between individual tests
- time needed for documentation of the measurement results.

There is only very limited scope for influencing the total time needed for the tests, as most aspects of the test procedure and its duration are defined by international standards.

In terms of the applied voltage tests, some manufacturers shorten the effective test duration per unit by simultaneously supplying the test voltage to multiple transformers that are connected in parallel. This method, however, comes with the risk that a weak insulation in one unit, which would become manifest as a rise in the test current, can easily be overlooked. However, insulation failure with a full breakdown would be reliably detected, as the test current would suddenly rise sharply and the test voltage would break down.

More significant reductions of the time requirements are possible through reducing both the initial set-up time of the system and the reconfiguration time between the individual tests. Automated switching using motor-driven high-voltage switches would be one way of saving time in a significant order of magnitude. To show this, testing with manual clamping of electrical contacts of the unit under test will be compared with testing using automated switching. The time needed for the different pre-tests of, for example, the insulation resistance, DC winding resistance and vector group, will not be considered here. These pre-tests can be conducted on a separate test station to save time.

Testing using manual contacts

When routine tests are conducted in a transformer test field where the contacts are manually clamped to the unit under test, the following steps must be performed as a minimum before each test:

- de-energizing the test field
- accessing the cordoned-off safety area
- taking protective measures to prevent electrical hazards (shorting and earthing)
- disconnecting contacts to be modified on the unit under test
- making the new contacts on the unit under test
- removing the protective measures (earthing rod)
- closing the barriers of the safety area
- switching on the test field

To estimate the number of disconnecting/reconnecting actions, *diagram 5* summarizes the typical connection options for the individual routine tests. Only one connection option can be used at a time.

The upper part of *diagram 5* shows the connections required for the applied voltage test (7), where the voltage is supplied to the high-voltage side of the unit under test (6). All of the three phases on the high-voltage side are jointly connected to the high-voltage transformer (5) of the test system. The connections of the low-voltage side are shorted and earthed for this test.

Much lower voltages are required for the applied voltage test on the low-voltage side; they can be tapped directly from the step-up transformer (2) of the test system. For this, the three phases of the low-voltage side of the unit under test are connected to the test system (9), and the high-voltage side (10) is shorted and earthed. An automatic switch in the test system connects the three contacts of the unit under test with the single-phase test voltage.

When the connections on the high-voltage side (10) have been removed, the induced voltage test can be started. For this, a voltage of about twice the nominal voltage and at least twice the nominal frequency is supplied to the low-voltage side of the transformer. This can be followed by a no-load test without the need to reconfigure the connections. The no-load current and the losses of the laminated core are determined during this test. In order to avoid any bias of the measurement result through any pre-magnetization that may be present, the no-load test is typically started at a voltage that is higher than the nominal voltage, and the voltage is then gradually reduced to the nominal voltage level. No-load tests are carried out at the nominal frequency of the unit under test.

Now, to determine the load losses in a load loss test, the connections on the unit under test need to be reconfigured again (8). The test voltage is supplied to the high-voltage side. The phase connections on the low-voltage side are shorted using a flexible cable that is as short as possible and whose cross section is as large as possible, because this test is conducted at the nominal current of the transformer. The load loss that is measured on the high-voltage side includes both the losses in the transformer itself and the losses in the short-circuit bridge and contact resistances. For this reason, particular attention must be paid to establishing reliable connections on the low-voltage side with the lowest possible contact resistance. This requirement can generally only be satisfied through correspondingly high contact forces that ensure a sufficiently high contact pressure. When the described sequence of steps is followed, the test field needs to be accessed five times, and the contacts of the unit under test need to be connected and disconnected again seven times altogether.

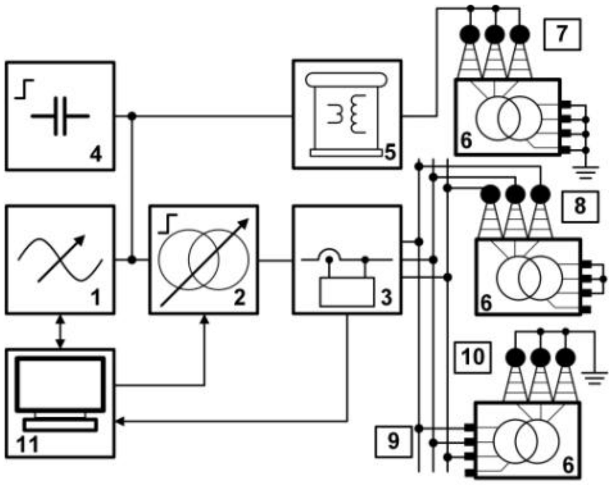

Diagram 5. Typical connection options during the routine testing of transformers

Testing using automated switching

If the transformer test field is equipped with motor-driven high-voltage switches that permit automated switching of the test circuitry, the number of manual steps carried out by the test personnel can be reduced dramatically. Once the contacts on the high-voltage and low-voltage sides of the unit under test are connected with the test system, the test field does not have to be accessed again between the individual tests. Consequently, not only can the time needed to rearrange the contacts be saved, but also the time needed to take the protective measures to prevent electrical hazards and the time to repeatedly disconnect and reconnect the power supply of the test system is no longer necessary.

Diagram 6 shows a possible circuitry for automated switching. The contacts of the distribution transformer (10) under test are connected with the test system using flexible cables. The switches shown in *diagram 6* are typically located above the test room, in order to reduce the space requirements of the test system on the one hand and, even more importantly, to keep the connection cables as short as possible on the other. The inverter system (2), which includes both the required filter stages and the elements of the capacitive reactive power compensation, is optionally used here again to feed a step-up transformer (1) or the additional high-voltage transformer (3). These connections are established automatically via low-voltage contactors.
With the six motor-driven switches (4) to (9), all of the mentioned test circuit arrangements to be set up without manual intervention. The switch positions for the individual tests on both high-voltage and low-voltage side are listed in *table 1*.

When testing a distribution transformer for the 36 kV medium-voltage grid, the required voltage rating of the switches (5), (6) and (7) on the high-voltage side is typically about 70 kV for the line-earth voltage during the applied voltage test and 72 kV for the line-line voltage during the induced voltage test. The required rating of the other switches (4), (8) and (9) does not exceed 5 kV. Since all switching operations are performed at zero voltage, and switching arcs do not have to be extinguished, inexpensive motor-driven open isolating switches would be appropriate both from a technical and cost point of view. However, the contacting systems of standard isolating switches used in general power supply applications only guarantee typically between 1,000 and 2,000 cycles which is not enough. By contrast, an automated transformer test field is designed for testing up to 10,000 transformers per year. To minimize the maintenance costs for the isolating switches, special disconnectors are used with a service life of > 100,000 cycles. These disconnectors comprise combinations of abrasion-resistant materials.

Special high grade drive parts and bearings ensure mechanical reliability. In contrast to the mechanical reconfiguration of the transformer contacts by the test personnel, the time needed to establish a new test circuit arrangement is only limited by the switching time of the motor-driven isolating switches. Depending on the voltage class of the switch, this time is between 5 and 10 s.

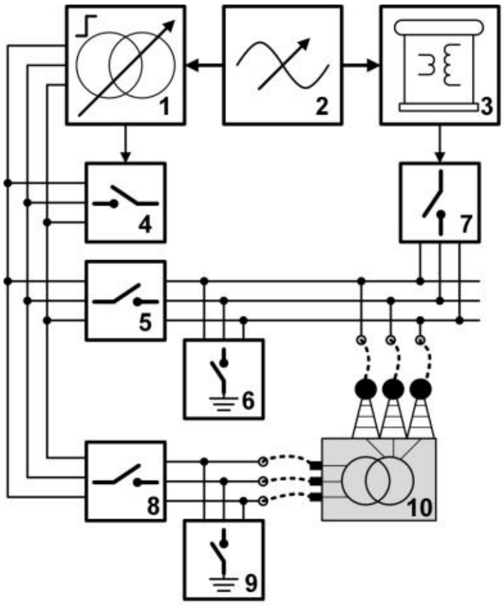

Diagram 6. Circuitry for automated switching during the routine testing of transformers

Switch positions		
HV test	LV switch closed	Switch closed
High voltage applied	7	9
Low voltage applied	6	4 + 8
Induced voltage	-	8
No load	-	8
Short-circuit loss	5	9

Table 1. Switch positions for the individual tests as per *diagram 6*

Test system control levels

As well as speeding up the test procedure with automatic switch-over devices, optimized system control design can also deliver time savings, particularly through efficient processing of measurement data and automated generation of test records. If, in addition, the internal data management of the test system is linked with the transformer manufacturer’s ERP system, the testing can be fully integrated into the manufacturer’s business processes. The manufacturer-specific document management system can then be used, for example, to manage the transformer data, to create test instructions and to log test results. Central evaluation of the test results of produced transformers would also open up many possibilities for quality assurance.

The control system can be divided into several hierarchically organized levels. This is shown in a simplified manner in *diagram 7*, where the levels are designated by the letters A, B and C. Each higher-level element is characterized by an additional degree of abstraction and greater distance to the hardware of the test system.

The lowest control level (A) comprises the internal PLC (3), which directly controls the test system (1) in conjunction with a graphical user interface (4). The test personnel (5) must enter all electrical parameters that are relevant for the test manually at this control level. The required internal settings of the system are then made automatically by the PLC. Adjustments for and analyses of the load loss measurement (2) and the high-voltage measurement also take place at this level. Thanks to the direct vicinity to the system hardware, special tests can be conducted here that differ from the standardized routine tests. The collected measurement results can be stored in a raw data format by the PLC and then output for further processing.

Thanks to an extended control system (B), which is based on a special PC software (6) and a system-specific database (8), the level of manual input required on the test system for a particular test is reduced to typing in the serial number of the transformer under test. The test instructions, which contain all data that are relevant for a particular test, are prepared separately in advance and stored in the database. All collected measurement results, including those of the pre-tests of the transformer, are also stored in this database and can be matched easily to the tested transformer through its serial number. Once all of the tests are completed, all data can be processed, combined and filed in a test record (7).

The highest degree of abstraction (C) is reached when the system-specific data management is linked through a coupling module (9) with the manufacturer’s ERP system (10). Such a coupling module, however, involves large investments and human resources for the installation, but also for continuous maintenance, to ensure trouble-free data exchange, in particular during unavoidable adjustments made to either system. Full integration, however, boasts the advantage that the entire production cycle of the distribution transformer, including all test instructions, measured data and records, can be centrally managed in one system. This makes it possible to reliably retrace all processes that are associated with the quality of the transformer at any time.

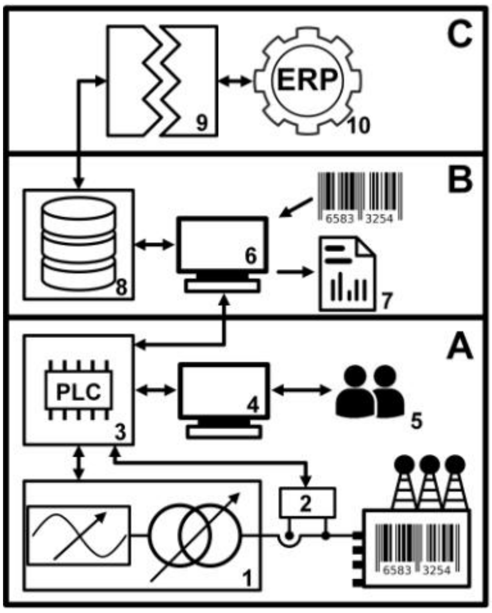

Diagram 7. Hierarchically organized levels during the routine testing of transformers

Diagram 8. Shop test of a DiTAS at HIGHVOLT using a platform lift before customer delivery

World-wide use under real production conditions

The modular concept of the DiTAS test system allows manufacturers and electric utility companies to offer bespoke and optimally-priced distribution transformer test solutions with short project completion times.
There are currently seven DiTAS systems in operation world-wide and customers are clearly very satisfied with HIGHVOLT’s latest product development. In particular, the straightforward manner in which HIGHVOLT integrates the complex test system into the existing customer infrastructure and the user-friendly operation are the subject of praise time and again.

As the size of the test object varies greatly depending on nominal power, parts of the test system are assembled on a height-adjustable platform lift (*diagram 8*) during configuration to ensure quick and uncomplicated connection to the test system. Together with the automated switching, full high voltage testing of a distribution transformer thus requires less than 15 minutes. Hence, it was possible to increase test field throughput in one-shift operation to 7,000 tests a year. Such a test system would be able to annually perform 20,000 full routine tests in four-shift operation.

This therefore proves that, by adopting automated testing together with an advanced control system, test field efficiency can be considerably increased with no detrimental effect on product quality. HIGHVOLT therefore makes a significant contribution to customer quality assurance.

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After successfully completing his studies at Coburg University of Applied Sciences, engineering graduate Thomas Steiner worked as a software developer and director in Dr. STRAUSS GmbH's DKD (German Calibration Service) calibration laboratory. In 2005, he took over leadership of the measuring technology team and has been technical lead at HIGHVOLT Prüftechnik Dresden GmbH since April 2007. He is also member of various national and international committees such as DKE K 124 (the high current and high voltage testing working group at the German Commission for Electrical, Electronic and Information Technologies) and the IEC 61083-1, -2 and -3 working groups, and is the German spokesman for IEC TC 42 as well as member of MT 07 and MT 16.

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