# ON-SITE REPAIR, REFURBISHMENT AND HIGH VOLTAGE TESTS OF LARGE POWER TRANSFORMERS IN THE TRANSMISSION GRID

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## 1. INTRODUCTION

Large power transformers at critical nodes in the transnational transmission grid are strategically important components. Their reliability is essential for the safe and stable operation of the whole power infrastructure. In Switzerland and in other countries of central Europe, the majority of the power transformers connecting the 400 kV and 220 kV transmission systems were installed in the 60's and 70's, i.e. they are more than 30 years old. Deregulation and the fast growing energy markets have led to a significant change in the seasonal and and/or daily loading patterns of these service aged units. In particular cases, such load patterns with peaks near or above the name plate loading capability may cause significant thermal stress in the active part of a transformer and, as a consequence, increases the risk of in-service failures with a forced outage. In addition to service and load conditions which significantly influence the ageing process and the reliability of a specific transformer, it can be concluded from statistical data, that failure rates of large power transformers are also dependent upon the highest winding voltage, i.e. upon the dielectric stress experienced in service. Typical failure rates for voltages up to 400-kV are in the range of 1% to 2% p.a. [1].

If a catastrophic failure occurs inside a large power transformer, remedial actions must be introduced within a short delay. The owner of the transformer must select, based upon economical and operational considerations, one of the following options:

- Replacement of damaged unit with a new transformer or with a spare unit
- Repair of damaged unit in the manufacturer's workshop
- Repair of damaged unit on site.

To support this decision process it is essential that advanced on-site diagnostic tools are readily available to assess and localise the damage in the active part of the transformer [2], [3]. Small on-site repairs on power transformers have been performed since many years. However, it is only recently that complete repair of large transformers have been reported including replacement of windings and insulation parts [4], [5]. This paper describes the failure incident, decision process and on-site repair actions on a 400 MVA transformer group in a 400-kV/220-kV substation with particular attention to the on-site diagnostic and high voltage testing procedures.

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## 2. FAILURE INCIDENT

Two 400 MVA transformer groups are installed in the substation Bassecourt to connect the European 400-kV grid with the Swiss 220-kV grid. In normal service, these transformer groups are operating in parallel. Both groups are of identical design and consist each of a 3-phase 400/220-kV autotransformer and of a 3-phase regulating transformer in two separate tanks (see Fig. 1). The regulating transformer includes a reversing load tap changer (LTC in separate oil compartment) and a series regulating winding (17 taps) on 220 kV potential, excited via the 50-kV tertiary system of the autotransformer. A built-in delta/star-selector switch acting on the exciting 50-kV system inside the regulating unit allows a variable voltage vector with a fixed 0°, 60° or 90° phase shift to be added to or subtracted from the 220 kV terminal voltage of the autotransformer.

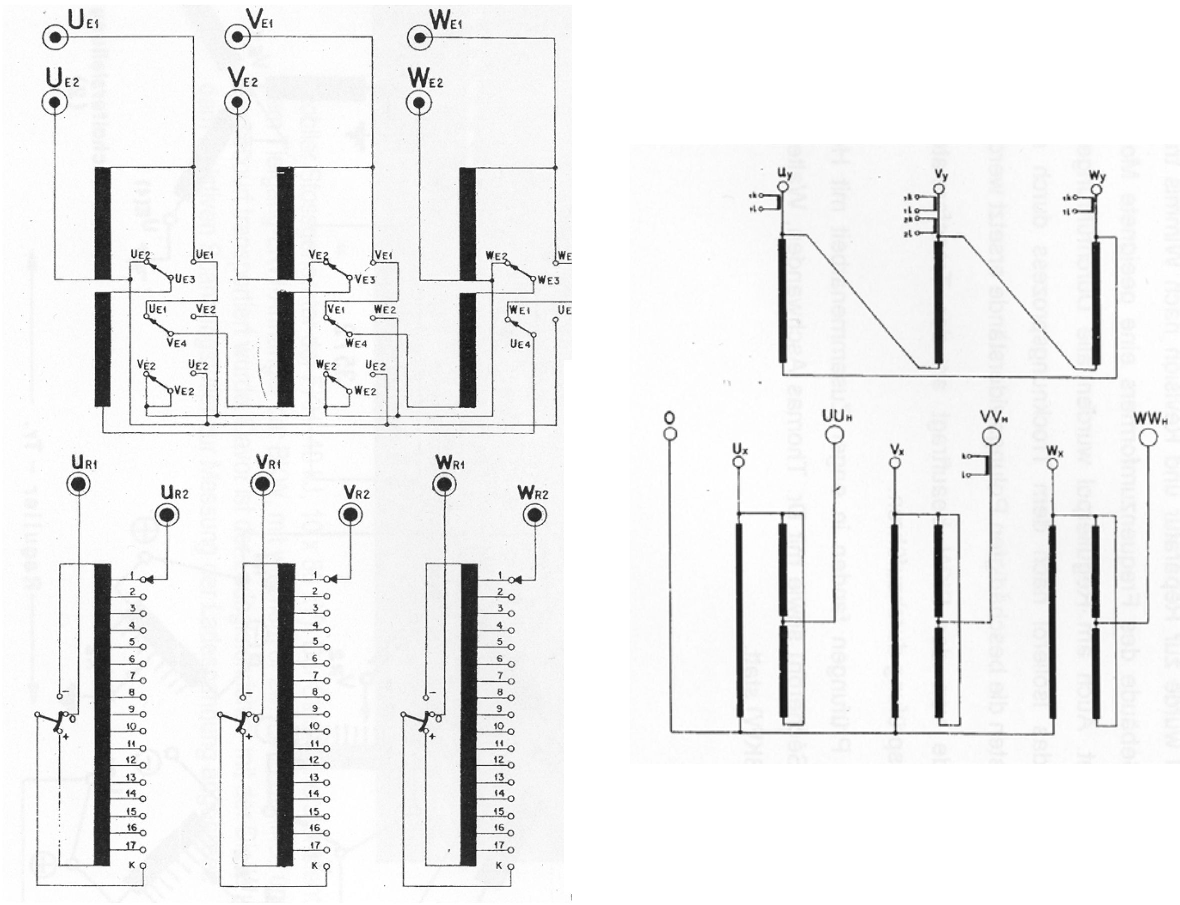


**Figure 1:** 400 MVA transformer group

The failure incident happened on 22.12.2001, 22.39 MEZ in a typical winter load situation with a highly fluctuating load flow peaking shortly before or after midnight (see Fig.2). At the time of the failure, both transformer groups were set to 60°-phase shift regulation and loaded with 76% (441 A at the 400 kV terminals) and 82 % (800 A at the 220 kV terminals) of the nominal phase currents.

A defect at the lower end of the 220 kV bushing (dry type) of phase V of the autotransformer (group #32) led to an electrical breakdown in the high voltage insulation. The high fault current at the 220-kV terminal of 15 kA (duration 62 ms) generated a steep overpressure wave inside the transformer tank. Through rupture of the porcelain insulator at the metallic flange, the bushing of phase V was expelled in an explosive manner. The whole transformer group was tripped by the differential protection relays and the Buchholz relay and disconnected from the grid within 85 ms. Thanks to the fact that bushing and 220-kV windings were connected through a multi-contact connector, this bushing "explosion" caused only little damage to the active part of the autotransformer.

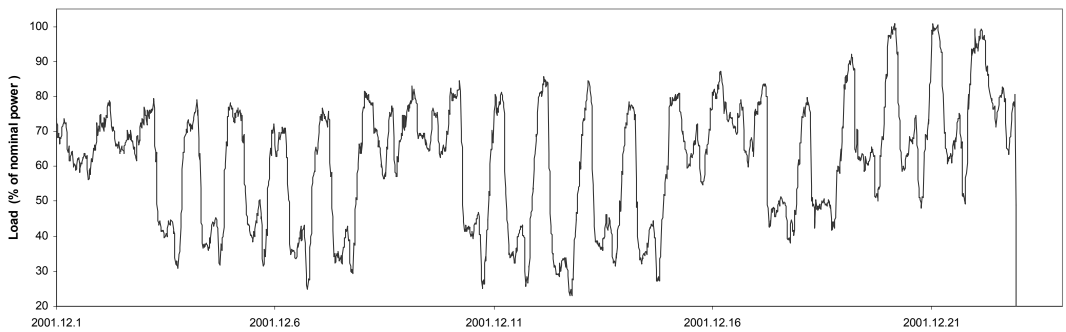


**Figure 2:** Load flow profile for a 400MVA group before the incident (22.12.2001)

After the trip of the autotransformer (group #32), the actual load was transferred to the parallel-connected transformer group #31. During a period of several minutes this group was loaded with approximately 150% of the nominal currents. With the intention to reduce this critical load, the LTC was activated to increase the impedance (from tap position 29 to 32). 8 minutes after the failure in group #32, the regulating transformer of group #31 tripped by the Buchholz relay protection: results of the gas-in-oil-analysis (DGA) indicated that an internal electrical breakdown or flashover occurred in this unit.

## 3. DAMAGE ASSESSMENTS AND DECISSION PROCESS

This critical outage of total 800 MW transformation capacity between the 400 kV and 220 kV grid could be handled mainly by re-dispatching the production schedules and by changing the grid topology without further consequences for the whole transmission system. However, an immediate action was necessary to recover at least partly the lost transformation capacity as soon as possible: it was decided in a first step to connect the autotransformer of the group #31 with the undamaged regulating unit of the group #32. Three days after the failure incident this transformer group went into operation.

The above-described damage at the 220 kV terminal of the autotransformer was assessed through close visual inspection inside the tank and through measurements using advanced diagnostic tools (see Table 1). This investigation led to the conclusion that the active part of this transformer, apart from the destroyed bushing and the damaged 220 kV outlet of phase V, had no further damage. In particular, the frequency response analysis (FRA) revealed no deformation of the windings. Considering the clear results of the damage assessment (damage restricted to phase V only) and considering the high cost and risk of transportation of this heavy unit (180 tons without oil) to the manufacturer’s workshop (large power transformer are no longer produced in Switzerland), it was decided to carry out the repair of the autotransformer on site without de-tanking the active part.

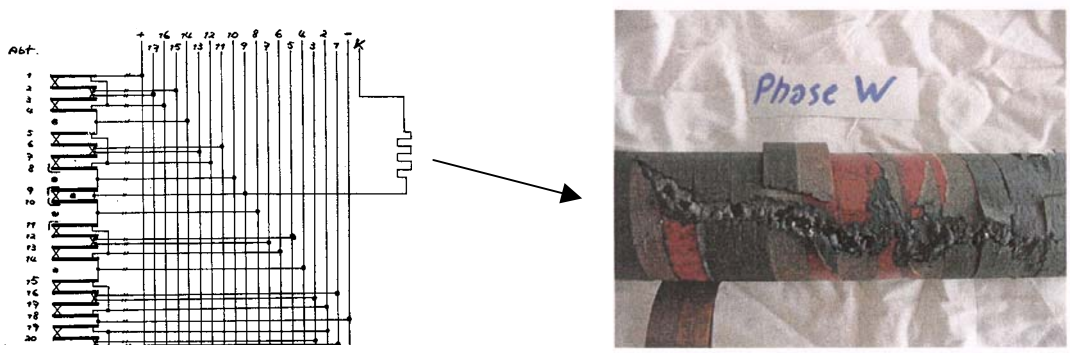


**Figure 3:** Damaged tie-in resistor of the regulating unit

The origin of the failure in the regulating transformer (group #32) was more difficult to find: a first inspection revealed no visible damage, however, the results of the dissolved gas-in-oil-analysis (DGA) indicated an internal electrical breakdown or flashover involving cellulose insulation material. Furthermore, resistance measurements indicated, that there might be a contact problem in the LTC-system. Therefore, this smaller unit (98 tons without oil) was transported to the transformer service facility of BKW in Wimmis (large hall with crane) for de-tanking and closer inspection. Here, the origin of the electrical failure was clearly identified in a AC voltage withstand test with 20% of the nominal voltage (no load), applied to 50 kV terminals of the de-tanked active part in air: the tie-in resistor of the tap selector (150 kΩ) of phase W was interrupted and caused an electrical breakdown (see Fig. 3). After the removal of the defective resistor the AC withstand test was successful. The rest of the active part, including the complicated regulating windings and the LCT-system, was found to be in an excellent condition. It was decided to carry out the necessary repair work and the high voltage tests at this BKW facility and to bring the repaired unit back to substation Bassecourt.

**Table 1:** Diagnostic tools and results for damage assessment

| **Method** | **Autotransformer Group # 32** | **Results** | **Reg. Transformer Group #31** | **Results** |
|---|---|---|---|---|
| **Winding-Resistance** | Deviation between actual and reference measurements less than 0.5 % (within accuracy of the method) | Good contacts<br><br>No short circuited windings | Deviations between actual and reference measurements | Deviations too large, typically 5 mΩ, active part must be inspected, in particular tap changer contacts |
| **Winding-Ratio** | Difference between measured and expected values within accuracy of the instrument (±0.1%) | No short circuited windings | Differences between measured and expected values within the accuracy of the instrument (±0.1%) | No short circuited winding |
| **Short Circuit Impedance (50 Hz)** | Deviation from reference values within accuracy of method < 0.5% | Core undamaged<br><br>No short circuited windings | Deviation from reference values within accuracy of method < 0.5% | Core undamaged<br><br>No short circuited windings |
| **Buchholz Gas** | --- | --- | Combustible gas and big amount of carbon monoxide | High energy arcing causing insulation damage |
| **Dissolved Gas in Oil Analysis** | High concentration of combustible gas with presence of acetylene | Arcing (high energy) | High concentration of combustible gas with presence of acetylene | Arcing (high energy) |
| **Frequency Response Analysis** | No difference between the responses of the three phases | Windings undamaged, no deformation | No difference between the responses of the three phases | Windings undamaged, no deformation |
| **Dielectric Spectroscopy** | No significant difference within the last measurement | Main insulation undamaged<br><br>Moderate aging of the main insulation | No significant difference within the last measurement | Main insulation undamaged<br><br>Moderate aging of the main insulation |
| **High Voltage Withstand Test** | --- | --- | AC test of the active part in air: 20% of nominal voltage, 30 min | Tie-in resistor of tap selector, phase W, damaged, indicated by white smoke |

# 4. REPAIR AN REFURBISHMENT

## 4.1 On-site repair of the autotransformer

Based on the results of a close visual inspection of the active part, some cleaning activities had to be performed inside the tank via manholes after removing the oil. Careful cleaning was done with hot oil to remove all debris and the peaces of cellulose insulation, which were distributed inside the tank due to the bushing explosion. Despite of the violent disconnection of the 220 kV bushing outlet, there was no indication about further damage of the winding-block. However, the complete outlet of phase V, including multi-contact-connecter, shielding electrodes and outlet-cable had to be replaced. Beside this, all bushings (400 kV, 220 kV, 50 kV, neutral terminal) were replaced. To avoid a similar bushing failure in the future, all three 220 kV outlets-cables have been modified with an improved insulation.

A critical element in all on-site repair activities of large power transformers is the drying procedure. It is well known that, due to the long time exposure (several days) of oil impregnated cellulose insulation to the air humidity, both the thermal and dielectric properties can be degraded. During service local humidity causes enhanced dielectric losses and free gas may be produced (bubbles) leading to dangerous partial discharge (PD) activity.

A combined drying process was applied to the active part including: (a) Hot oil circulation (90° C) with subsequent vacuum phase for extraction of the absorbed water from the cellulose insulation, and (b) low frequency heating (LFH) of the windings to dry the winding insulation. With the application of four drying cycles (5 days per cycle) a total of 13.3 liters of water was removed from the active part. The target value for water removal to finish the procedure was set to $< 0.5$ liters/day.

## 4.2 Repair of the regulating transformer

The replacement of all tie-in resistors and of all high voltage bushings (epoxy type with compound insulator) was the main repair activity at this unit. The design of the tie-in resistors was significantly improved: (a) better mechanical stability using an epoxy instead of ceramic carrier tube, (b) lower current density and lower thermal stress using a NiCr wire with larger diameter and class H insulation. As these resistors are permanently connected to the regulating winding, they are also exposed to significant electrical stress during transient over voltages. Therefore, all resistor elements were tested with 125 kV full and chopped lightning impulses.

As mentioned in the section 4.1, a reliable drying process is the key factor for the successful repair.
In a preliminary drying cycle, it was attempted to use "hot oil spray treatment" to heat up the active part inside the transformer tank. However, it was difficult to reach a homogeneous temperature distribution of the active part. Therefore, the same combined process for drying of the active part was used as described under 4.1 before refilling the transformer with new oil.

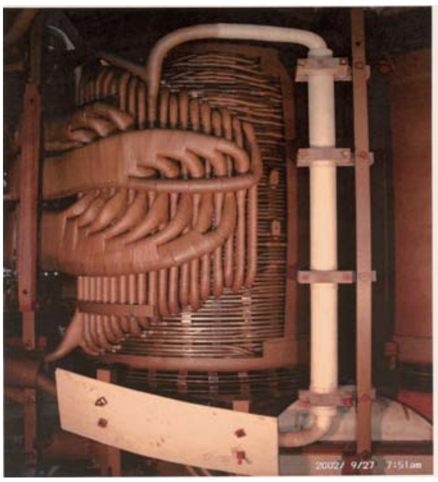


**Figure 4:** Replaced tie-in-resister

## 5. DIAGONISTICS AND HIGH VOLTAGE TESTS AFTER REPAIR

Repair work carried out under difficult on-site working conditions needs an extensive quality assurance program. In our case two categories of methods were applied: (a) specific diagnostic methods to check process results (drying) or important components (bushings), and (b) high voltage tests on the complete transformers to ensure the dielectric integrity. An overview of the methods applied is given in Tables 2 to 6.

**Table 2:** Applied Diagnostic tools for quality assurance during repair

| Goal | Method |
|---|---|
| Control of the drying process and the solid insulation properties | Thermography during drying process |
| | Water outlet during drying process |
| | Dielectric Spectroscopy |
| Control of the oil properties | Dissolved Gas in Oil Analysis |
| | Physico-chemical properties of oil |
| | C-Tan delta measurements |
| Control of the connections | Winding-Resistance |
| | Winding-Ratio |
| Control of the pressure of the windings | Frequency Response Analysis |
| | Short circuit Impedance |
| Control of the bushings | C-tan delta measurement |

**Table 3:** Lightning impulse tests on the complete transformer group (tap changer position 35)

| | |
|---|---|
| **Performed test** | Single phase lightning impulse test on the complete transformer group (220 kV terminals connected) using a mobile lightning impulse generator (see Fig.5)<br>7 positive polarity impulses of 660 kV applied to 220 kV terminal of regulating unit<br>7 negative polarity impulses of 660 kV applied to 220 kV terminal of regulating unit<br>Amplitude of 660 kV corresponds to 120% surge arrester voltage at the 220 kV bus bar |
| **Results** | Comparison of the lightning impulse waveforms at 60% and 100 %.<br>No breakdown or dielectric fault was detected during 14 lightning impulses applied to each phase |

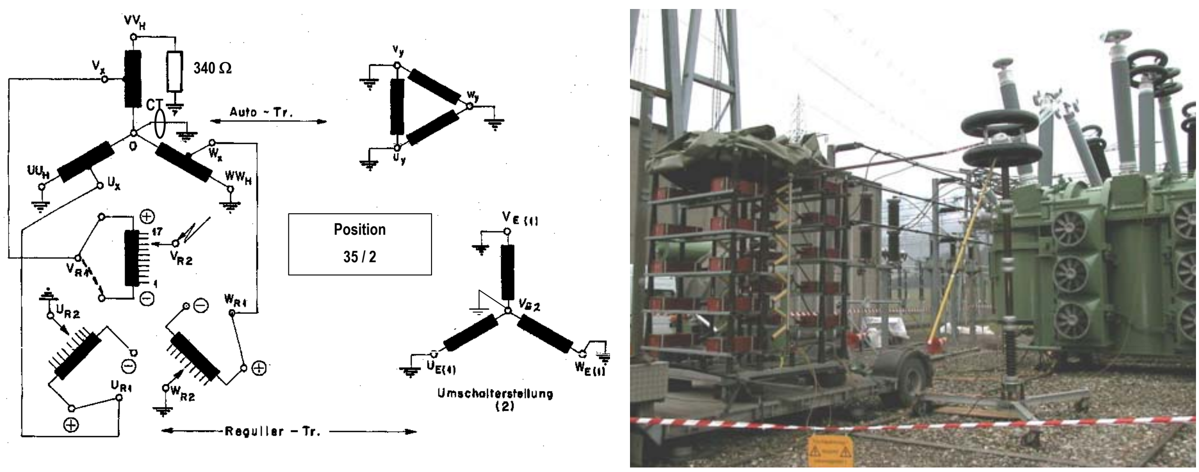


**Figure 5:** Setup for the lightning impulse test

**Table 4:** Induced voltage test on the autotransformer

| | |
|---|---|
| **Performed test** | Three phase excitation via 50 kV tertiary windings with mobile diesel generator-set up (60 Hz) and step up transformer<br>PD-measurement at 110% $U_n$ on 400 kV windings, 220 kV windings, neutral and tertiary windings. |
| **Results** | PD-activity was detected at the repaired 220 kV bushing at 100 % $U_n$ (see Fig.6a), this PD-pattern is typical for bubbles in the insulating system caused by the local humidity [6]. After a further drying cycle this PD-activity extinguished (see Fig.6b). Due to the limited power of the generator-set the shape of the test voltage was strongly destorted by harmonics. |

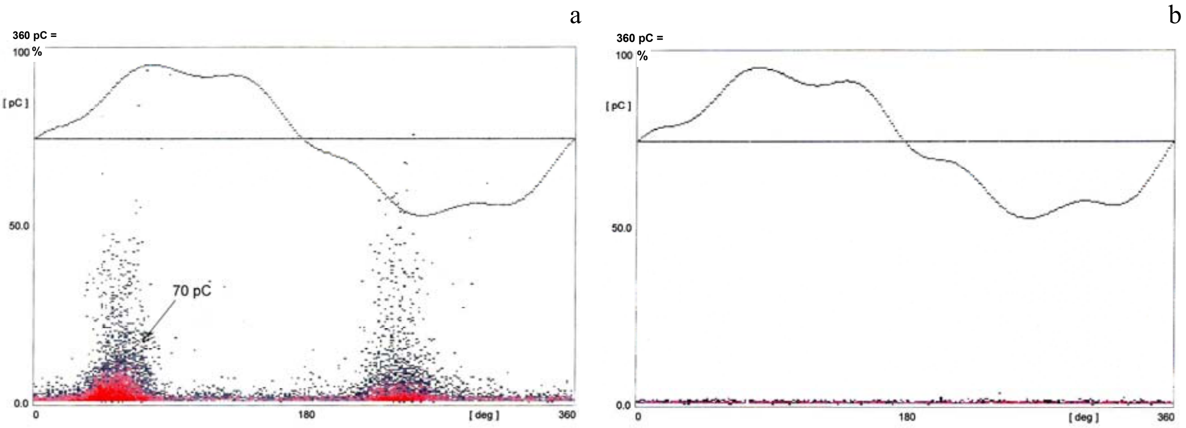


**Figure 6:** PD-activity at 220kV terminal phase V: (a) before and (b) after the last drying cycle

**Table 5:** Induced voltage test on the regulating transformer-tertiary winding

| | |
|---|---|
| **Performed test** | Three phase excitation via 50 kV tertiary windings with mobile diesel generator-set up (60 Hz) and step up transformer<br>Dielectric test of the tertiary winding only, no PD-measurements |
| **Results** | The tertiary winding passed the induced voltage test without any problem |

**Table 6:** Applied voltage test on the regulating transformer

| | |
|---|---|
| **Performed test-on the regulating winding** | Series resonance test circuit (resonance frequency between 110 and 119 Hz). Single phase test (see Fig.7).<br>PD-measurement at 110 % $U_n$ on 220kV windings and tertiary windings |
| **Results** | No PD-activity was detected. After alle modifications and repair work, the insulating system of all three phases is in an excellent condition. |
| **Performed test on the tertiary winding** | Series resonance test circuit (resonance frequency 94 Hz). All six bushings were connected together.<br>PD-measurement at 110% $U_n$ on tertiary windings via external coupling capacitance |
| **Results** | No PD-activity was detected. After all modifications and repair, the insulating system of the tertiary winding is in an excellent condition. |

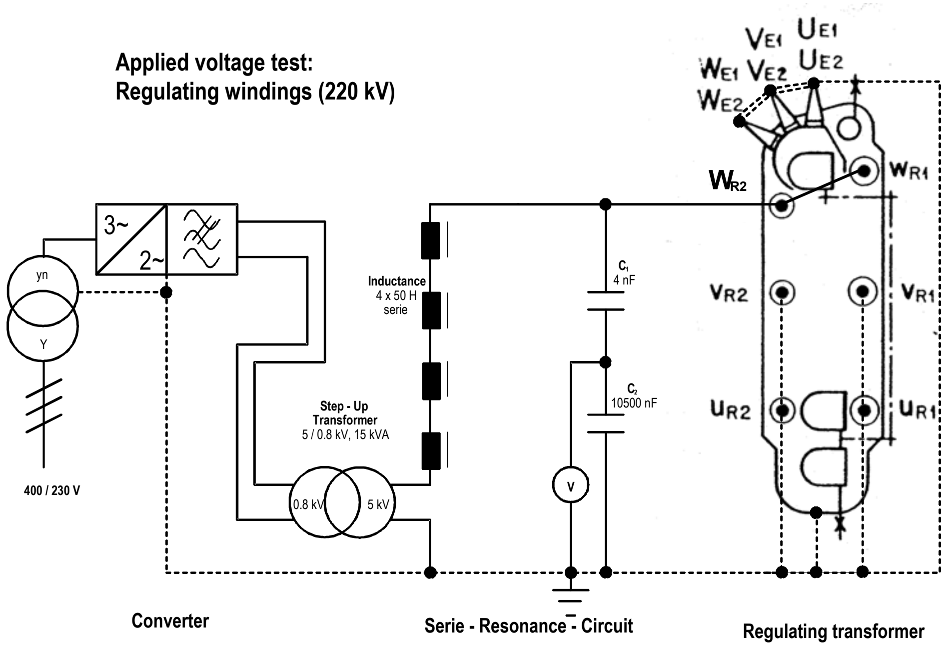


**Figure 7:** Circuit for the applied voltage test, example phase W

## 6. CONCLUSIONS

Since December 2002, exactly one year after the unexpected outage, the transformer group is in service again. Its load is close to 100% for a few hours every day. This case has demonstrated that advanced on-site diagnosis methods are important both for the reliable and economical decision process and for the quality assurance during the repair process. A well controlled drying process is essential for the successful repair of large active parts on site.

In order to avoid another unexpected incident with these refurbished units, it was decided to install a simple and reliable on-line monitoring system on both units. The following parameters are now continuously observed: (a) transformer load, (b) oil temperature, (c) dissolved gas in oil (mainly hydrogen) and (d) water in oil content. For each transformer, all the information is collected by only one commercial measurement system. These devices are interconnected together with a serial network and can be remote controlled through a modem connection.

## 7. REFERENCES


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