

Equipment for ON-Site Testing of HV Insulation

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EQUIPMENT FOR ON-SITE TESTING OF HV INSULATION

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Abstract

On-site testing has often been requested by the utilities following installation of new HV cables, and also to check the condition of HV power transformers suspected of a damaged insulation.

Specialized equipment for on-site tests has to withstand off-road transportation, to pass under road-bridges, be equipped with its own power source, and what is most difficult, to make measurements at HV substations which are notorious for intense electromagnetic interference.

At present, a HV resonant test set-up with the partial discharge (PD) measuring instrument, and the C-tg δ bridge with built-in test voltage source are the most frequently used mobile test equipment.

This paper presents a mobile HV resonant test set-up for installed cable testing, and measuring instruments designed for on-site transformer insulation testing.

1. INTRODUCTION

1.1 Resonant test set-up

Considering a large capacitance of the HV cable line, and a high test voltage level, the resonant test set-up is the only practical test voltage source. It can provide the required high reactive power to the examined cable, and it draws only a small active power from the supply source.

Different design options of such resonant test set-up have been proposed for on-site testing of HV power cables. Initially, the capacitive reactance of the examined cable was compensated at power frequency, by an inductive reactance of the HV reactor with a mechanically regulated gap in the magnetic core. This design is still employed at HV laboratories for testing short cable sections. However, the weight and size of a controlled gap reactor preclude its use as a mobile test set-up for on-site testing of long cable sections.

The first resonant test set-up composed of a fixed HV reactor, but a variable frequency voltage supply was developed twenty years ago [1], for commissioning tests of gas insulated substations (GIS). A relatively small capacitance of the test object has required only a modest output power. The first variable frequency mobile resonant

test set-up was composed of four reactors rated each at 200 kV, 1.2 MVar (10 min. load), and such rating was sufficient to test GIS.

An order of magnitude higher output power is available from the modern, variable frequency, mobile resonant test set-up [2]. This is a major improvement, since for the first time the resonant test set-up provides a sufficient output power to test a few kilometer HV cable line, such as encountered in power transmission systems. An original design of the test set-up composed of two reactors rated each at 220 kV, 14.5 MVar (60 min. load) is described in the following paragraphs.

1.2. C-tg δ bridge for on-site measurements.

Reliability of HV power transmission systems depends largely on the reliable operation of power transformers. Experience has shown a surprisingly long life of some HV power transformers in service. A CIGRE study has revealed a significant number of such transformers operating satisfactorily for more than 40 years. On the other hand, an impressive service record of paper-oil insulation resembles a "time-bomb" situation, where the transformer integrity depends on an aged paper and contaminated oil.

Utilities would like to keep older transformers in service, but check the condition of their HV insulation. The most common procedure consists in periodic checks of the dielectric loss factor - tg δ , and capacitance - C of the transformer paper-oil insulation.

Although the C-tg δ bridge was invented by Schering more than half a century ago, its operation in HV substations is hampered by the strong electromagnetic interference. The original version of this instrument has been modified to enable on-site periodic checks of the transformer insulation. The conventional decade resistors and capacitors were replaced by the current comparator circuit which reduces the effect of such interference, and the bridge was equipped with a portable test voltage source regulated up to 12 kV.

1.3 HV insulation recovery voltage measurements

Besides the C-tg δ bridge, another instrument may be employed to assess an overall degradation of the transformer paper-oil insulation, using the dielectric polarization effect.

The polarization recovery voltage method (RVM) allows for an assessment of the water content in the paper-oil transformer insulation, and also helps to reveal an aged insulation. However, the recorded recovery voltage waveforms have to be evaluated by a skilled operator. In particular, paper-oil insulation composed of a multilayered structure may produce results, which do not correspond to the reference curves obtained on samples of dielectric material.

2. ON-SITE TESTS OF XLPE HV CABLES

2.1 Standards and established practice

After-laying tests of XLPE cables rated at 220 kV and 400 kV have not yet been covered by international standards [3], but a test specification was proposed by KEMA, the leading Dutch HV research and test institution.

According to KEMA, a new 400 kV XLPE cable after installation has to be stressed with $2 \times 400 / \sqrt{3} = 462$ kV test voltage applied for 30 minutes. This test may also be performed by applying 420 kV for 120 minutes, according to the proposed IEC 840 Standard. A mobile test set-up was executed with a rated output power of 29 MVar, and this allows for an application of 440 kV test voltage for 60 minutes.

2.2 Design features of the mobile, variable test frequency resonant test set-up

Several important factors have to be taken in consideration while designing a resonant test set up for on site testing to ensure its reliable operation under all circumstances occurring during transportation and testing.

Figure 1 shows the circuit diagram for a resonant test set with variable frequency. The frequency converter (1) is supplied with three phase, power frequency voltage, and generates a single phase rectangular pulse of a variable repetition rate, and a controlled pulse width. The repetition rate is adjusted to the resonance frequency of the HV reactor (3) connected to the examined cable. Impedance of this circuit is very low at resonance frequency, but large at higher harmonics. In consequence, the test voltage waveform at the cable terminal is close to sinusoidal [4].

The frequency converter generates intense disturbances, which may reach some nC, during the semiconductor switching. A complex filtering system (2) has been developed to ensure a disturbance free voltage supply. Using such a filter, partial discharges can be measured on the cable under test without gating and/or windowing of the recording instrument. This solution is preferred with respect to other design based on blocking the PD detector at the time of the frequency converterswitching.

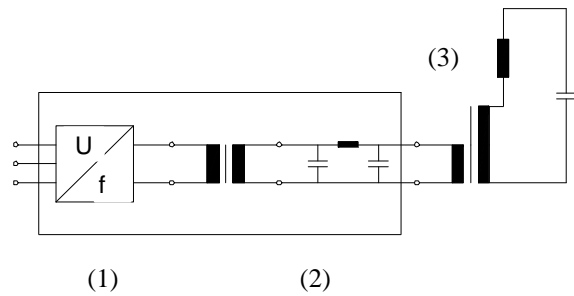


Figure 1 Circuit diagram of a resonant test set with variable frequency

A detailed analysis of the electric field distribution inside the oil tank was carried out with the aid of the Weidmann reference curve method [5], as illustrated in Fig. 2. The safety margin derived from these calculations was increased to account for the lower dielectric strength of oil, reduced by shaking during the road transportation. Nonetheless, a certain rest period is required after the trailer installation on the site, before an application of the test voltage.

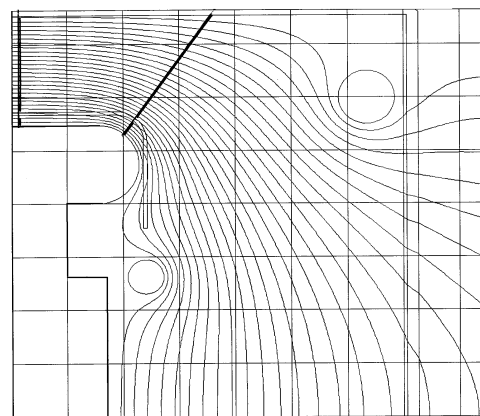


Figure 2 Electric field distribution at the reactor top electrode. A safety margin of paper-oil insulation was checked along the trajectories marked on this field plot, using the Weidmann reference curve method.

Thermal capacity of the winding has been dictated by the resonant test set-up duty cycle: 1 hour-"on", 2 hours-"off", up to 6 cycles in 48 hours. Oil forced, air forced cooling system was adopted to keep the winding and oil temperature rise within the 60°K and 65°K limit, respectively. These temperatures are very conservative for a test set-up, since they are normally specified for power transformers with 30 year life expectancy.

A ratio of the reactive power S oscillating in this resonance circuit, and the active power P supplied to cover the losses, determines the circuit factor $Q=S/P$. Owing to the high Q factor, usually exceeding 100 for XLPE cables, a limited power drawn from the mobile motor-generator set is sufficient to generate the required high reactive power in the cable under test.



Figure 3 After-laying test of 420 kV cable with the aid of the mobile test set-up. One HV reactor and coupling capacitor standing on the trailer and the second reactor on a platform isolated for 220 kV.

The complete resonant test set-up can be moved on a platform to the cable installation site, as it is shown in Fig. 3, and perform the required test in a relatively short time. The cable manufacturer who acquired this mobile test system has already performed more than 100 tests.

3. ON-SITE TESTING OF THE OF HV POWER TRANSFORMER INSULATION

3.1. C-tgd bridge for periodic checks of HV insulation of transformers in substation.

An invention of the capacitance and the dielectric loss factor (C-tgd) measuring bridge by Schering in 1920-ies, enabled an early detection of incipient faults in paper-oil insulation of HV transformers. However, the Schering bridge low voltage part composed of decade capacitors and resistors, as well as the vibration galvanometer operate at the millivolt level. Even a modest stray capacitance between them and a near by HV bus bar results in stray currents induced in the sensitive bridge circuits. Such interference effectively precludes the Schering bridge operation in HV switchyards.

An introduction of the current comparator, invented by Kusters and Petersons in the 1960-ies, reduced the effect of stray capacitance between the bridge low and high voltage circuits. The current comparator is composed of the primary and secondary windings wound on a toroidal magnetic core in such a way, that the ampere-turns of the primary tend to cancel the ampere-turns of the secondary winding. A tertiary winding is wound on an inner core made of a high permeability material, and installed inside the main core. The tertiary winding detects an imbalance magnetic flux in the comparator core, but is shielded against the stray flux of the primary, as well as the secondary winding.

At the balanced condition, there is no magnetic flux in the comparator core, and the primary and secondary windings have very low input impedance, determined by

the resistance of copper wire. This low input resistance makes the current comparator naturally immune to electromagnetic interferences.

The current comparator with an additional system of power amplifiers has been implemented in a portable C-tgd bridge [6] designed for operation in substations. This bridge comprises a test voltage source regulated up to 12 kV, which supplies the examined HV transformer insulation. A current flowing through the insulation is brought to the first winding of the current comparator, shown in Fig. 3 on the left side of the core.

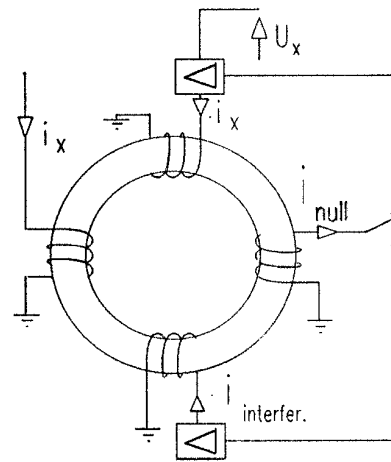


Figure 4 The current comparator at input stage of the C-tgd bridge effectively reduces the electromagnetic interference from HV circuits.

At first, the bridge is operated with the test voltage switched off, and the input current i_x is induced only by the electromagnetic interference. The imbalance detecting winding (shown in Fig. 4 on the right side) provides the current i_{null} to the lower amplifier. The amplifier generates a current $-i_{interfer}$, which cancels the interference current i_x . This interference canceling current is then “frozen”; i.e. is maintained during the whole measuring session. Subsequently, the test voltage is applied to the examined insulation, and the input current i_x is then composed not only of the interference, but also of the sought current from the test object. The i_{null} signal is then switched to the upper amplifier, which produces a current equal to $i_x - i_{inter}$, being the replica of the sought current.

Effectively, the current comparator separates the sought current of the examined insulation from the interference current [6]. The current comparator also provides an output voltage U_x proportional to the sought current.

3.2. Transformer paper-oil insulation ageing assessment based on the recovery voltage method.

An ageing of cellulose and increased water content have an influence on the insulation dielectric polarization properties. An assessment of the cellulose insulation can be derived from the polarization frequency characteristic, however it is quite difficult to perform such measurements on a transformer in substation.

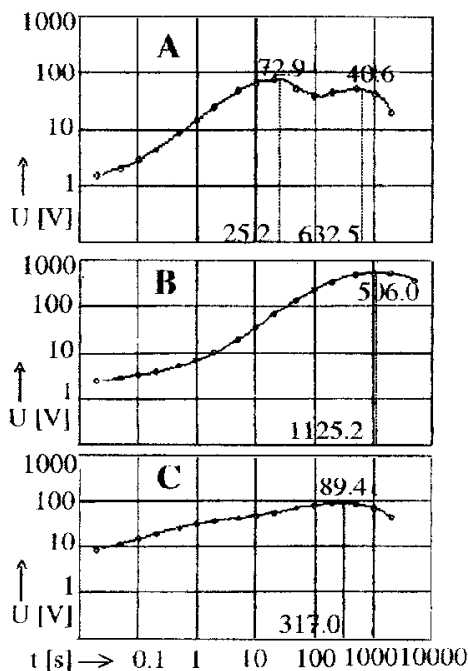


Figure 5 The polarization recovery voltage as a function of charging time. The first graph A reveals a maximum which precedes the peak corresponding to the normal ageing. The first maximum indicates a premature ageing of paper in a particularly exposed area, whereas the whole bulk of paper insulation is much less affected. The two other curves B and C show only one hump, which indicates a normal ageing process.

The time (rather than frequency) domain method has been proposed by Hungarian research team [7], and implemented in an instrument for measurement of the polarization recovery voltage. The instrument applies a direct voltage to the examined insulation for a sufficiently long time to polarize the dielectric, and then this voltage is suddenly removed. A relaxation of dielectric material produces a recovery voltage (or current in an external circuit) which is initially increasing at a certain rate, and then decreasing to zero.

As shown in Fig. 5, a maximum recovery voltage occurs at a certain time, which is an indicative of the insulation ageing, and of the water content. A quantitative assessment of the insulation condition should be based on a comparison of the recovery voltage waveform recorded on a new transformer and after a certain time of service.

An interpretation of readings obtained on a HV transformer in substation requires a certain knowledge of the examined insulation geometry, and in particular the relative thickness of paper and oil space in the stressed paper-oil insulation.

6. CONCLUSIONS

- Owing to the increased capacity of mobile resonant test set-up, after laying tests can be performed on the highest voltage XLPE cable lines. The HV reactor constitutes the critical part of such set-up, and recent improvement of the reactor design enabled an on-site testing of 400 kV, 4 km long XLPE cable line.
- Periodic checks of the transformers in substation include a measurement of $C\text{-tg}\delta$ of the paper-oil insulation. A special bridge was developed for on-site measurements of $C\text{-tg}\delta$ with an interference suppression circuit based on the current comparator principle. A portable source of 12 kV test voltage is integrated with this bridge.
- An instrument was developed for an on-site assessment of the transformer insulation water content and ageing, based on the dielectric polarization effect.

7. REFERENCES

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