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TRANSFORMER BUSHING – A PART OF MEASUREMENT SYSTEM

SUMMARY

Power transformer is one of the most important and most expensive components in the electric power system (EPS) and requires, from its production and throughout lifetime, continuous monitoring and checks of the availability in the power system. All the measurements and tests on the transformer which manufacturers attempt, in order to determine the quality of their products, are carried out through the connection of different types of bushings, and these measurements and tests are conducted in accordance with requirements of applicable standards. Also, the owner of the transformer during the exploitation phase wishes and needs to know the status and availability of transformers for future work. The only available points of the transformer inside are the bushings. The technical practice from the early beginnings of the transformers are periodic off-line measurements. Following that practice and experience, the need arose for continuous supervision of transformer operation (on-line). In the 90's the first simple systems for the transformer on-line monitoring appeared. Today, it is an established fact that the modern systems for on-line monitoring of transformers provide a complete insight in the transformer state including alarms in the case of critical states. It is realistic to expect in the future that these same systems, apart from providing diagnostics and giving alarms, will be authorized to switch off transformers in the case of necessity with high degree of confidence. An important role in on-line monitoring, as a part of measurement system, has a transformer bushing. For the purpose of both off-line and on-line measurements, manufacturers of the bushings are equipping them with the measuring tap. Unfortunately, despite intentions to standardize the components of the power system, this is not the case with the measuring tap, and the intention of this paper is to draw attention to these problems and to try to find a solution.

Key words: power transformer, bushing, measuring tap, on-line monitoring, test

1. INTRODUCTION

Bushing is an important component of the transformer, and very often their number can be more than ten per transformer. They function as links between transformer windings and the network with the purpose of raising the voltage level suitable for power transmission with minimum losses, and then lowering the voltage to the level appropriate for the consumer. Price of these bushings in the total price of the transformer can even reach up to 10%. Unfortunately, the bushings are the most common cause of transformer failure, often accompanied with disastrous consequences (explosion of the bushings, transformer fire, ...). Depending on the category of failure, according to some statistics, the participation of a bushing fault to the outage of the transformer reaches up to 50%.

Among many divisions of bushings, for indoor or outdoor installation, the basic division is by the type of insulating medium:

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- Oil – Air
- Oil – Oil
- Oil - SF_6

The second division is performed by the internal construction:

- Capacitance graded bushings (for voltages ≥ 52 kV) - bushings in which a desired voltage grading is obtained by an arrangement of conducting or semiconducting layers incorporated into the insulating material
- DIN bushings (distribution voltage levels) – bushing in which the major insulation consists of ceramic, glass or analogous inorganic material.

Capacitance bushings, the main subject of this article, according to IEC 60137:2008 [1] are divided into:

- Oil-impregnated paper bushings (OIP)
- Resin-bonded paper bushings (RBP)
- Resin-impregnated bushings (RIP)

When selecting the bushing, it is important to have information about the measuring tap (test tap, voltage tap, *tan*δ tap) such as the maximum voltage that may occur in normal operation and load that can be connected to the measuring tap. If the measuring tap is not in use, it must be directly grounded. Also, each capacitance graded bushing must have the data of the main capacitance (C_1), the capacitance of the measuring tap (C_2) and dielectric dissipation factor (tanδ). Values of the capacitances (C_1 and C_2) are dependent on the constructive solutions of the bushing producers, while the value of tanδ is defined in the standard with the criteria according to [1], Table 8 - Maximum values of tanδ and tanδ increase.

2. HIGH VOLTAGE MEASUREMENT SYSTEMS

To use a transformer bushing as a component of a HV measurement system, the bushing has to be condenser type and must have a measuring tap, and all its capacitances and transfer characteristic must be known. The whole measuring system (bushing, measuring impedance, cable...) must have resonance frequency exceeding at least 500 kHz. A simple way to check frequency response of the measuring system is to use recurrent surge generator or a sweep generator and compare input and output voltages, as shown in Figure 2 and 3.

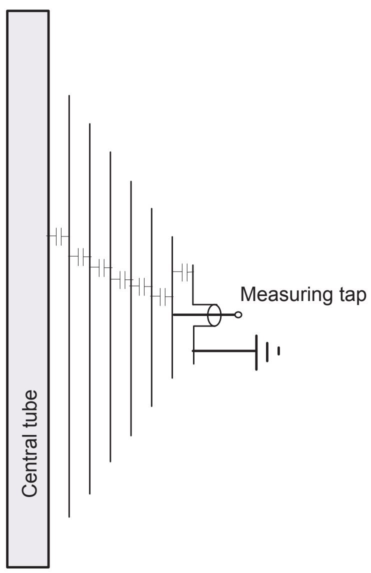

Figure 1 - Capacitance graded bushing

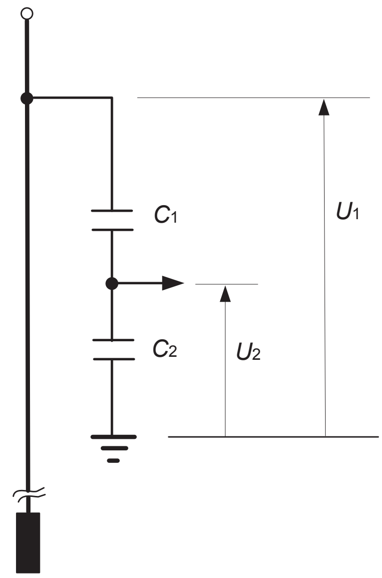

Figure 2 – High voltage divider

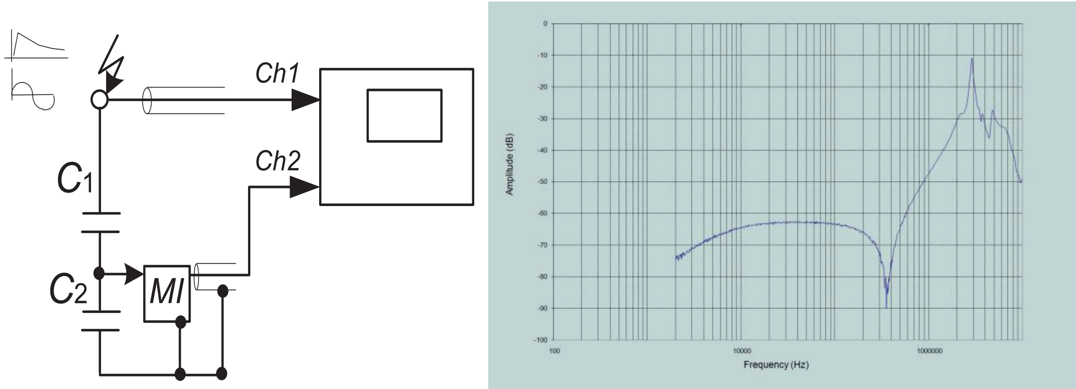

Figure 3 – Principle of checking the transfer characteristics of the measuring system with the bushing and the typical response

Transformer bushing as a component of the measurement system is used for the following tests:

- induced AC voltage tests (ACSD, ACLD), IEC 60076-3: 2000 [2], Clause 12
- lightning impulse voltage test (LI) – IEC 60076-3: 2000, Clause 13
- switching impulse voltage test (SI) – IEC 60076-3: 2000, Clause 15
- on-line monitoring of *C*, *tanδ*
- on-line monitoring of partial discharges
- on-line monitoring of transient overvoltages

2.1. Induced AC voltage test

To verify the quality of each manufactured transformer, it must pass routine tests.

One of the most important test is induced AC voltage test.

Depending on the highest voltage for equipment U_m applicable to a transformer winding and on the rated insulation level for all transformers with $U_m \geq 72{,}5$ kV, ACSD test is normally performed with partial discharge measurements to verify partial-discharge-free operation of the transformer in service conditions.

Time sequence for application of test voltage for induced AC voltage test with measurement of partial discharges is shown in figure 4.

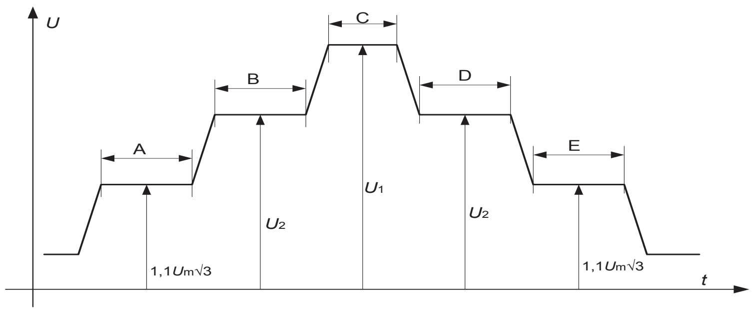

Figure 4 - Time sequence for application of test voltage for induced AC test with measurement of partial discharges.

We can use bushing in two ways:

- as HV capacitive dividers for measurement of applied voltage, and
- coupling capacitor for measurement of partial discharges.

For measurement of AC applied voltage we must know C_1, C_2. Values of capacitances C_1 and C_2 are mostly in pF range, and usually C_2 has a higher value.

All instruments for measurement of peak value/√2 have maximum input voltage up to 150 V, and if we want to measure a higher voltage, we have to modify the HV divider in figure 2.

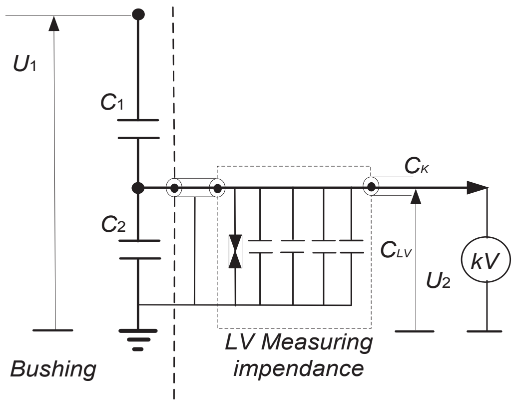

Figure 5 – Measurement configuration according to IEC 60060-2:2010 [3]

$$U_1 = p \times U \tag{1}$$

$$p = \frac{C_2 + C_{LV} + C_K + C_1}{C_1} \tag{2}$$

where: p – divider ratio (scale factor of kV)
C_2 – capacitance of measuring tap
C_{LV} – capacitance of measuring impedance
C_K – *capacitance of coax. Cable*
U_1 – test voltage of transformer winding

Alternative method for measurement of test voltage during AC test is shown in figure 5. This method is recommended for on-site testing of power transformers, because in many cases it is not possible to make a test in the same conditions like the one in the test station in the factory.

2.2. Measurement of partial discharges

If we use the alternative method for measurement of AC voltage, one way to measure partial discharges is to use transformer bushings as coupling capacitors. Another methods, e.g. using an additional coupling capacitor, are very complicated for connection of the tested transformer, require up to six coupling capacitors and a big area for test arrangement. Regarding sensitivity, the best way to measure is to use bushings.

The method of measurement and test arrangement is shown in figure 6.

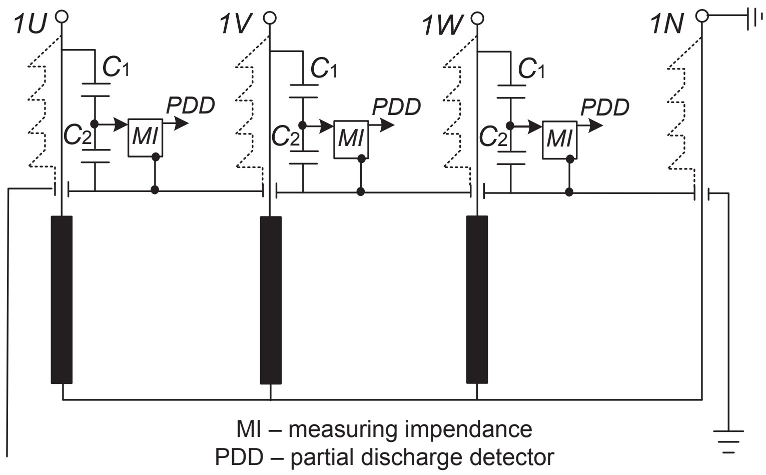

Figure 6 – Principle of measurement of partial discharges on power transformer via bushing

Measuring impedance (MI) has to be placed near the measuring tap of bushing and well earthed. All connections between measuring tap, measuring impedance and partial discharge detector must be with coaxial cable.

The type of measuring impedance depends of its purpose. Today we have integrated solutions that include measurement of partial discharges and measurement of voltage.

Type of measuring impedance is shown on the figure 7.

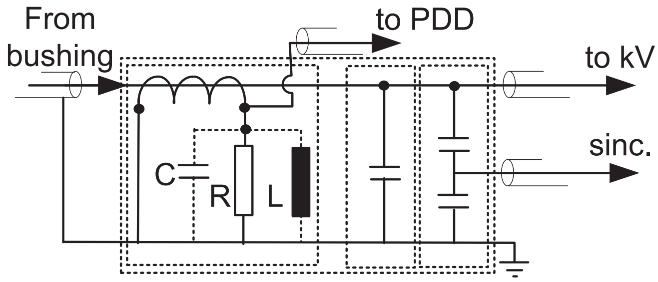

Figure 7 – Measuring impedance for measuring PD and voltage

2.3. Impulse test

Impulse test is one of dielectric tests for verification of quality of transformers for different service conditions.

In factory tests all transformer manufacturers use bushings as HV measurement system, especially in switching impulse withstand voltage tests. During the preparation of test circuit the shape of the applied switching impulse has to be in accordance with IEC 60076-3:2000, but the shape also has to give good distribution along tested and untested windings. The difference between tested and untested terminals must be less than $1{,}5U_t$.

The test circuit for the adjusted shape is given in figure 8.

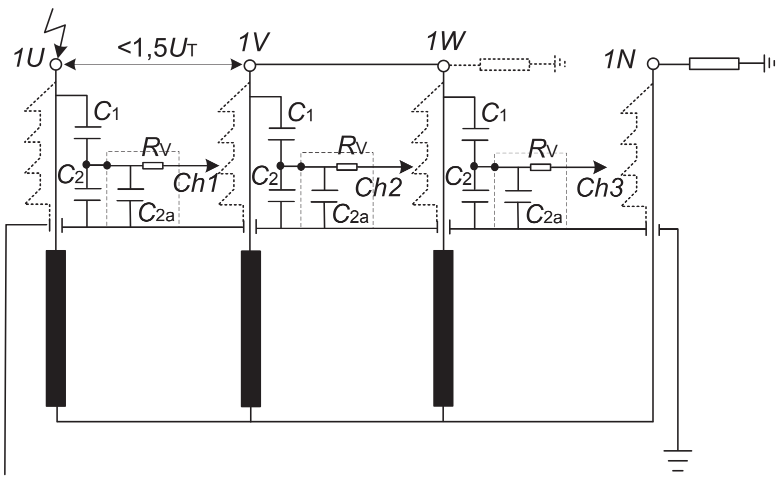

Figure 8 – Test circuit for switching impulse test – adjusted shape of impulse wave

2.4. On-line transformer monitoring

In the previous section we analysed the measuring facilities in which we can use transformer bushings for measurements. Also, the bushing can be used for on-line monitoring. During the last ten years we can find different solutions for on-line monitoring systems, which all require connection to the measuring tap of bushing, for example:

- On-line monitoring of the bushing (*C*, tanδ)
- On-line monitoring of the transient over-voltages
- On-line monitoring of the partial discharges

For all those solutions of on-line monitoring systems, the HV measuring circuit has to be prepared. The voltage level on the measuring tap has to be adjusted for measurement and registration. Connection between measuring tap and the measuring impedance must be solidly earthed and waterproof, what is very difficult to achieve.

Another problem is that there are many designs of measuring taps. Each producer of high voltage bushings has their own type of measuring tap and sometimes even the same manufacturer has several designs of measuring taps.

All manufacturers of on-line transformer monitoring systems encounter this problem especially if they have to mount on-line monitoring system on a transformer in service (retro-fitting).

3. DESIGN OF THE MEASURING TAPS AND THE ADAPTERS

Measuring tap is placed on the bottom part of bushing, near the bushing flange.

There are lots of designs of measuring taps, but more recently they are of cylindrical design with the thread on the inner or the outer part of the cylinder. Figure 9 shows some of the measuring tap designs of the well known bushing manufacturers.

Figure 9 – Different designs of measuring taps (from left to right: Končar OTF type, ABB Micafil type, Passoni-Villa type)

Measuring tap can be integral part of the bushing (non removable) but it can also be removable as shown on figure 10.

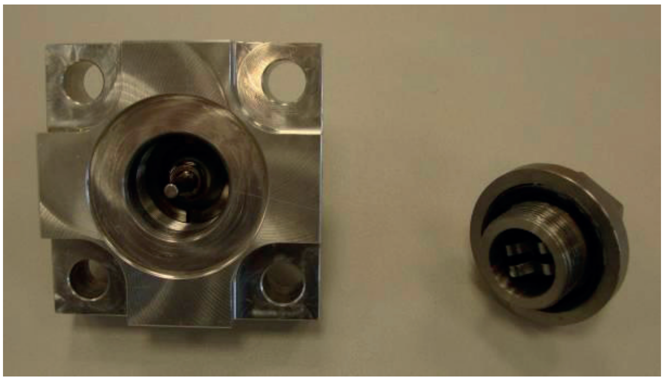

Figure 10 – Measuring tap with the protective cover

Internal connection of the tap depends on the overall construction but it is usually connected to the last capacitive layer of the bushing via spring needle or a wire. The overall capacitance between the power line connection of the bushing and the measuring tap is usually labeled as C_1, and the capacitance between the measuring tap and the ground is labeled as C_2. If the measuring tap is not in use, it should be grounded with the protective cover (bypassing the C_2). Ungrounded measuring tap during the normal operation of the transformer can result in severe damage.

The use of the measuring tap for periodic off-line measurements is not so demanding like the use for the on-line monitoring systems. Since those systems are supposed to monitor several quantities of the transformers over the longer period of time, the permanent connection to the test tap is required. This is assured with the specially designed adapters. The adapter connects the tap with the measuring impedance via short patch cable, as shown in the figure 11.

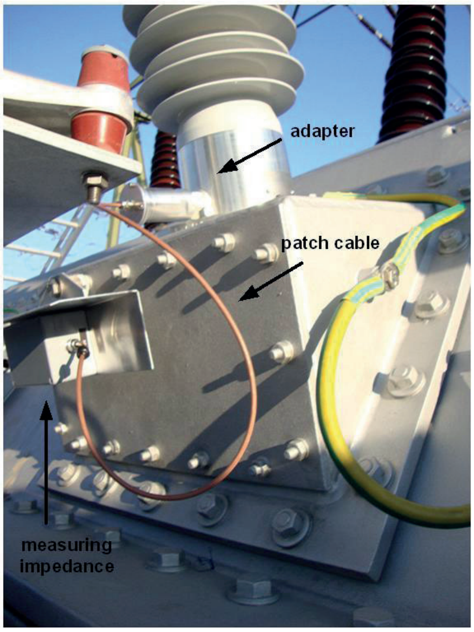

Figure 11 – Adapter and measuring impedance for on-line monitoring purpose

Water penetration is very common problem in this application. Water can create conductive layer between the contacts in the adapter and/or measuring impedance therefore making the measurements non valid. More importantly, water can make severe damage to the contacts of the adapter or the measuring impedance, resulting in an open tap condition. Therefore, the adapter must be waterproof and the special attention should be paid to the connection points of the patch cable. Figure 12 shows how water can easily penetrate into measuring impedance, which is supposed to be completely sealed, and cause severe damage to the components.

Figure 12 – Problem of water penetration

The measuring tap adapter should have protective elements (like GDT's) between the main connection (tap connection) and the ground in case that it looses connection with the measuring impedance, which is the same case as the open (ungrounded) measuring tap. There is also problem of the compatibility of the materials. The measuring taps of older designs are usually made of silumin which is very soft material. Taking into account that all threads are made with some tolerances and that the old measuring tap threads are usually filthy and could already be slightly damaged, the adapter made of the harder material can make permanent damage to the measuring tap thread. This can be manifested in two ways. Either the adapter is stacked to the measuring tap (practically a cold welding point) or the adapter can be removed with some force, but the protective cover could not be inserted anymore, resulting again in an ungrounded tap condition.

Each design of the measuring tap requires differently designed adapter. That fact, as well as the fact that some of measuring tap designs are not suited at all for the continuous on-line measurements, represents big problem for the manufacturers of the on-line monitoring systems.

3.1. Proposals for the standardization

The focus of this article will be on the two possible designs types of the measuring tap and the corresponding adapters.

First design is based on the classic cylinder type with the inner thread not smaller than M30, possibly with the fine thread pitch (like M30x1.5). The front surface should be big enough for the gasket of the adapter. The tap itself should be 4 mm in diameter, which is very common value in the current designs. The center line of the measuring tap should be at least 70 mm above the bushing flange, or the earthing screw, for the easy manipulation with the adapter. The tap should not protrude more than 5 mm outside the gasket surface, otherwise the adapter would be too long (figure 13).

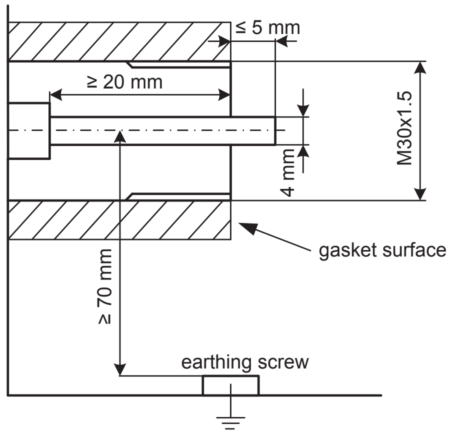

Figure 13 – Proposed dimensions for the measuring tap with inner thread

The adapter and the measuring impedance set for this configuration is shown in figure 14.

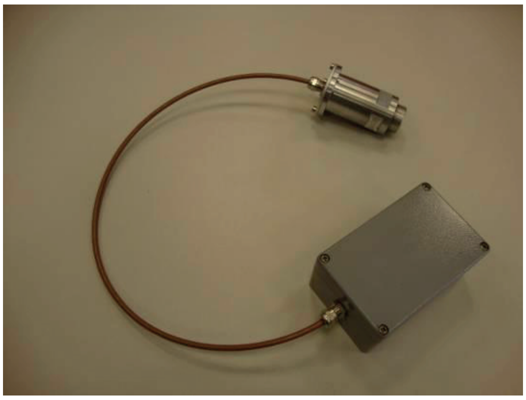

Figure 14 – Adapter and the measuring impedance

Due to the problem of the water penetration, the adapter and the measuring impedance should be completely sealed with the water repellent polyurethane compound, as shown in the figure 15.

Figure 15 – Measuring impedance components sealed with water repellent compound

The patch cable should be coaxial type with the high operating temperature (like the RG142) and it should be connected to the adapter and the measuring impedance through a cable gland, so the ends of a cable are also sealed. With this design, the adapter, patch cable and the measuring impedance are forming one unit which is slightly difficult to install, but the experiences so far are showing that even the high quality connectors, that can be mounted at the ends of the patch cable, are not the guarantee that the water will not penetrate. The other end of the measuring impedance, towards on-line monitoring system, should have the connectors with the IP protection as high as possible.

The variation of this design is shown in the figure 16.

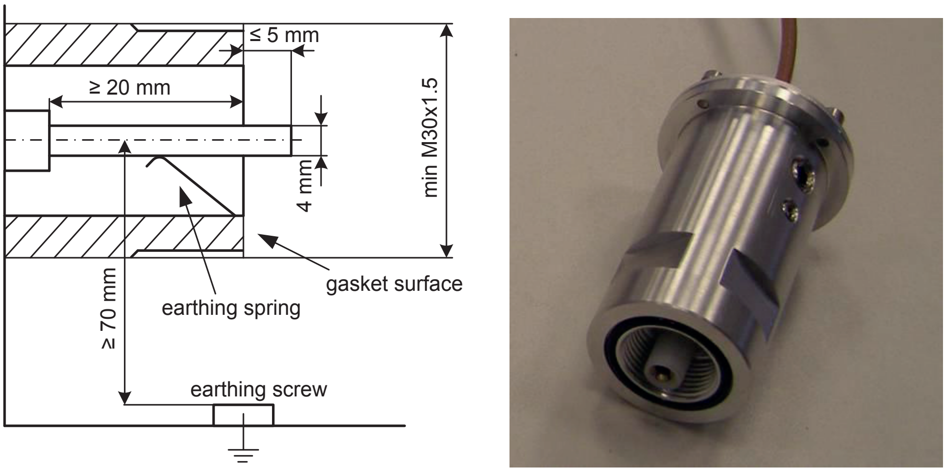

Figure 16 – Proposed dimensions for the measuring tap with outer thread and the corresponding adapter

This design has the outer thread due to the fact that some bushing manufacturers like to use the protective spring that will automatically ground the tap if it is left open. However, all the requirements for the measuring tap and the adapter with the patch cable and the measuring impedance are the same as mentioned above.

The potential problems of this design are the possibility of thread damage and the damage of the patch cable. Due to the potential damage of the patch cable, the adapter must have protective elements (surge arresters), like GDT's, built in.

The figure 17 shows the measuring tap of an old ASEA bushing.

Figure 17 – Measuring tap on ASEA bushing from 1965.

Although this is very old design, it is surprisingly practical for the purpose of the on-line monitoring and it is the base for the second design proposal. The firm connection with the tap is ensured by screwing the wire lug at one end, while the other end of the wire is connected to the measuring impedance. The measuring impedance is integrated in the protective cover, which is mounted to the bushing with the four bolts, and the gasket between the cover and the measuring tap base. The cover should be big enough to easily fit the PCB with the measuring impedance components and the surge arresters. Although the type of the components and their number depend on the measuring impedance purpose (voltage measurement, overvoltage detection, partial discharge measurement, tanδ measurement...), from the past experience, the cover with the inner surface of the 110x100 mm and the depth of 60 mm should be enough. Once the PCB with the components is mounted inside the cover, it should be sealed with the water repellent polyurethane compound. The connector on the outer part of the cover, towards on-line monitoring system, should have IP protection as high as possible (figure 18).

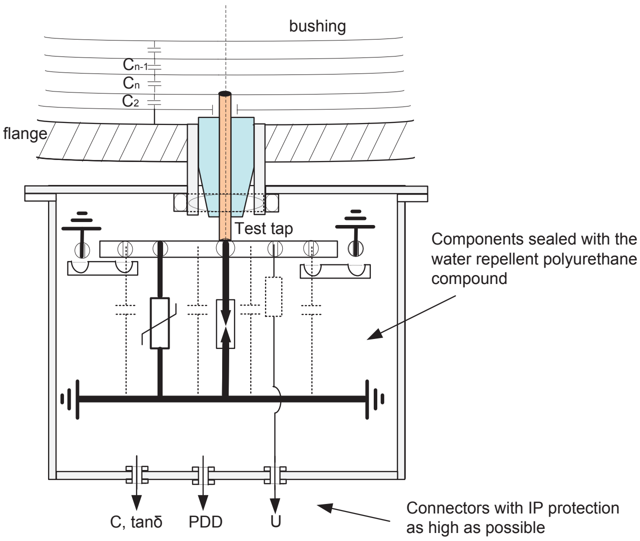

Figure 18 – Design proposal of the measuring tap with integrated measuring impedance

This kind of design has several advantages. The adapter, the patch cable and the measuring impedance from the previous example are all integrated in the cover. Therefore, there are no potential problems of the thread damage or the damage of the patch cable, which makes this design safer for the bushings and the transformer. Also, this solution is much easier to install and is a personal favorite of the authors of this article.

4. CONCLUSION

The importance of on-line monitoring systems has significantly increased in the last few years. Some of the most important measurements on the transformer are taken from the bushing measuring tap, where the bushing is a part of an overall measuring system. The current situation on the market with numerous measuring tap designs is unacceptable from the perspective of on-line monitoring systems manufacturers. The authors of the article have proposed some of the possible designs as a base for the debate and hopefully a new standard. Our goal is to find the solution which will satisfy both, the bushing manufacturers as well as the on-line monitoring manufacturers.

REFERENCES

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[3] IEC 60060-2:2010, High–voltage test techniques – Part 2: Measuring systems