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Heating MV Cables to the Exact Temperature for Combined Test

***Abstract**. The paper describes methods of direct and indirect heating of MV or HV cables for combined voltage tests. There is a description of commercially used principles, including the possibility of improving indirect induction heating. The purpose of our research was to solve the problems with uniform temperature distribution along the heated conductor and design the principle of non-destructive temperature control and measurement.*

Streszczenie.** W artykule opisano metodę pośredniego I bezpośredniego podgrzewania kabli MV i HV w badaniach testowych. Celem pracy było rozwiązanie problemu zapewnienia jednorodnego rozkładu temperatury oraz pomiaru I sterowania temperatury. **Metoda podgrzewania kabli MV do dokładnej temperatury w badaniach testowych

Keywords: MV Cable; HV Cable; Induction Heating; Temperature Control.
Słowa kluczowe: kable MV, podgrzewanie indukcyjne, testy.

1. Introduction

Diagnosis and withstand test of high voltage (HV) and medium voltage (MV) cables are an integral part of basic routine tests, development tests and type tests in high voltage testing laboratories. Overall, the cable tests can be divided into two categories. The first category is focused on mechanical tests, such as bending tests, climate chamber cycling tests, or mechanical and chemical resistance tests of cable top protect layers. The second category is electrical testing. PE, HDPE, XLPE and EPR insulation cables are tested and diagnosed in accordance with standards IEC 60840, IEC 60502-2, IEC 60885-3, IEC 62067 and IEC 60230. However, procedures for testing the quality of insulation are based on testing methods developed at TU Graz according to DIN VDE 0276-620 [1]. The set of applied tests consists of withstand combined tests, diagnostics (partial discharge - PD, dissipation factor - tan delta) [2], and finally cable breakdown voltage test to determine the residual electrical strength of dielectric [2-5].

Withstand voltage tests (Impulse voltage tests) are carried out as combined tests. This means that the cable is applied withstand AC or impulse voltage and at the same time cable conductor (core) is heated to the maximum temperature under normal operating conditions increased by 5 to 10 °C. This test temperature is determined by the maximum warming of the cable core at nominal and by sharing the heat with the surroundings. Also heating the cable core with a short circuit current is a very fast phenomenon. The cable core maximum permissible temperature is higher (PE 130 °C, HDPE 160 °C, XLPE and EPR 250 °C) for 5 seconds. In practice, there is no heat sharing with insulation or the surroundings in the first few seconds. Most modern HV and MV distribution network cables have working insulation made of XLPE material (cross-linked polyethylene). The maximum temperature of this insulation is 90 °C (HD 70 °C, HDPE 80 °C and EPR 90 °C). This means that the combined tests XLPE cables are performed at a core temperature of 95 to 100 °C. This paper describes various laboratory applicable methods of cable heating, principles of temperature measurement and regulation. All designs, measurements, are carried out in the CVVOZEPowerlab laboratory [4].

2. Applied principles of cable core heating

This paper is focused on the description of various principles of cable heating with temperature measurement and regulation. Warming the HV cable core by passing the rated current is relatively slow process, and heat is shared with the insulation materials and surrounding space. However, the fast and short time short circuit current will cause immediate heating due to Joule losses in the material of core. So the insulation temperature is identical to the temperature before the short circuit current flows. It has been practically measured that the insulation temperature is equal to the maximum ambient temperature of the cable with an increase of about 20 to 30 °C due to power losses in cable core by the nominal current. However, the heat begins to spread from the current conductor of the cable through individual layers of insulation and shielding to the surroundings very quickly after the passage of the short circuit current. XLPE insulation at the point of contact with the thin semiconducting layer surrounding the core will temporarily reach approximately the same temperature. The insulation temperature continues to decrease due to heat conduction through the cable against the temperature gradient from the core to the cable surface. The heat is shared from the surface by convection, radiation, and partially by conduction at the point of mechanical contact. Simulation of heat transfer and temperature distribution of individual layers in dependence on time for XLPE MV cable 150 mm^2 18/30 kV is shown in Figure 1. The cable core temperature is considered 100 °C and the ambient temperature is 20 °C - nominal atmospheric conditions. Surface jacket temperature is approx. 65 °C. The thermal conductivity of XLPE insulation material is approximately 0.32 W.m^{-1}.K^{-1} at 20 °C and 0.24 W.m^{-1}.K^{-1} at 100 °C. Thermal conductivity of semiconductor carbon-loading XLPE screen layer ranges from 0.3 to 0.8 W.m^{-1}.K^{-1} and XLPE loaded with 40 % of carbon is between 0.4 and 0.5 W.m^{-1}.K^{-1} [6, 7].

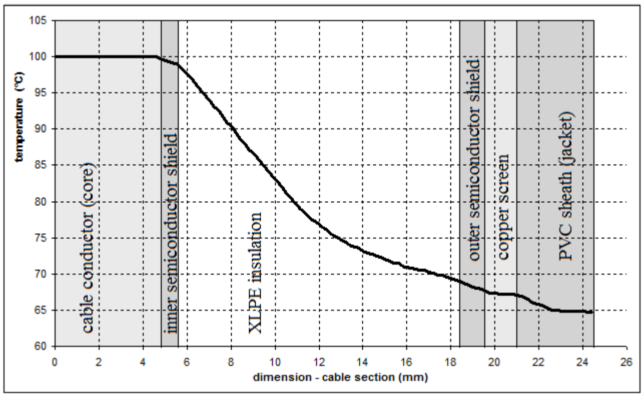

Fig.1. Temperature distribution in individual layers in XLPE 150 mm^2 18/30 kV MV cable - simulated data in ANSYS

Practical simulation of these processes is very complicated and impossible in practical implementation. In theory, the required current must first flow through the cable for required time to achieve maximum temperature of the core. Then the measurements should be triggered synchronously and withstand voltage tests started. Unfortunately, it is not possible to implement this procedure in the laboratory mainly due to the fact that the high current generator is usually unavailable in the HV laboratory. At the same time, this high current generator would have to allow galvanic connection to the potential of the high voltage test source output. This is also the reason why other methods are chosen in the laboratory to achieve the required heating of the cable core. These methods can be divided into a large group of active and passive methods.

2.1. Active heating methods

Active cable heating methods for combined tests are the most widely used. According to the principle and the measurement capabilities, these methods can be further divided into groups with and without galvanic isolation.

2.1.1. Cable heating by high current source

The most commonly used method of heating MV and HV cables is resistive heating, based on the flowing of alternating or direct current with an increased value, often 3 to 10 times the nominal current of the cable. In this configuration, the core of the tested cable is galvanically connected to a power source implemented as a transformer with magnetic circuit or as a switching source. The heating speed is influenced by the current value selection. The influencing factor is also the heat transfer around the cable as well as the maximum steady state temperature, which corresponds to the temperature at about 1.75 to 3 times the nominal current. However, this value is significantly influenced by the cable construction, in particular the thickness of the insulation layers and the screening material used. In addition, cable laying and ambient atmospheric conditions affect the final result. Steady state is achieved when the mean core temperature measured at least in 5 points does not change by more than 1 °C in 600 s or by 3 °C in 3,600 s. The recommended heating time for most MV cables with a core cross section of 95 to 500 mm^2 is between 1 and 5 hours, depending on the accuracy of the stabilization. [1] Unfortunately, it is very difficult to determine the actual value of the current, which can cause the core warming to the desired temperature. There is also a substantial impact of external conditions - temperature and air humidity. The laying of the cable, usually on the floor of the test room, significantly affects the heat transfer from the core and thus extends the heating time. For specific cable types, approximate heating current values can be found. However, practical experience has shown that the resulting temperature uncertainty is more than 20 °C, which is unusable for the purpose.

Heating current of effective value higher than 5 times the nominal value is chosen more frequently. At these values, the necessary warming can be achieved in a very short time, sometimes less than 10 minutes. However, the locally core temperature can significantly exceeds the desired/set value. Thermal and consequently mechanical damage of the cable, asymmetric displacement of the core or formation of gas capsules can be occurred as a result. Temperature measurement and thermostatic control must be used to avoid these negative effects.

The current source can be implemented as a switching source, typically with a DC output or as a source with a voltage decreasing transformer with alternating, one or two way rectified output. A current source of 1 to 3 kA with a voltage drop of up to 3 V DC or 10 V AC output is required for heating 10 to 30 m MV cable samples with a core cross section of up to 500 mm^2. The considerable voltage difference between AC and DC is due to the reactance of the cable, which only occurs when AC is used. The power factor correction (PFC) on the primary side of the transformer must be performed when using the AC heating. Unfortunately, the use of current sources for combined cable voltage tests has a significant limitation due to the galvanic connection of the tested cable core to the secondary side of the source. Connecting the ground potential to the cable core and output from the test source to the cable copper screen may be an alternative. However, this is not recommended due to safety concerns. The procedure also does not correspond to the actual connection of voltage potentials, and is not recommended by test regulations, guidelines and standards. There are only two options left. The first is the realization of a current source with a secondary output with sufficient galvanic isolation (impulse withstand voltage of at least 200 kV and alternating withstand test voltage of at least 80 kV for most MV cables). However, the current sources are very expensive and inefficient due to the high magnetic field dispersion. Secondary winding insulation is usually massive, single-piece made of teflon or polyethylene.

The second and often used heat procedure is based on the following principle. The heating cable core is done up to a temperature of 5 °C higher than the desired/required temperature. This is followed by a quick disconnection of the heat current supply and cable connection to the voltage test source output. These methods allow quick execution of the necessary diagnostics or short withstand voltage tests. The remaining time for the test is approx. 200 to 300 s. During this time, the cable core temperature decreases by 10 °C. This procedure is not recommended for accurate measurements. However, the test is normally applicable, taking into account other external influencing factors in other types of heating.

2.1.2. Cable heating by induction

The induction heating of a HV and MV cables is based on the same logic as the heating by current source. The method is based on a simple transformer. The primary winding of this transformer is powered from a regulated power supply and the secondary winding is a tested cable, respectively cable core forming one or more short circuit turns. The system operates at nominal 50/60 Hz mains frequency and the one side of test cable copper screen is connected to ground potential. This achieves a perfect galvanic isolation of the heating circuit and the high voltage test circuit. The high voltage potential of the cable core is connected by screen to ground potential in the event of cable breakdown during testing. This is a major advantage of using inductive heating of HV and MV cables, especially for combined tests. Unfortunately, most of the benefits are over. The realization of the measurement as well as the possible determination of the core temperature is much more complicated than the previous method.

The regulation of core warming or the achievement of a specific temperature is the same as the previous method. The core of the cable is heated again by the flowing current, resulting in Joule losses. A certain value of current can be (based on experience) determined for warming to the required core temperature.

However, from a practical point of view, it is preferable to select a current value greater than 5 times the nominal value of the cable. This provides faster and more accurate heating. However, this principle must be controlled by automatic core temperature measurement and control. The transformer used for heating is realized as bushing type, usually in toroidal form. Primary winding is rated for phase or line voltage of the power supply. And one turn of the secondary winding is typically in the range of 0.5 to 2 V. The heated cable usually passes only once through the transformer magnetic core. A voltage of about 3 to 10 V is required to achieve sufficient heating current in the cable loop. Therefore, it is necessary to use more toroidal transformers to achieve the required voltage. More transformers will also provide a more uniform energy flow to the cable loop along the entire circuit. Eddy current heating also has a small effect at the point where the cable passes through the transformer. This problem is minimized by the use of multiple transformer pieces. Simulations showed that the core temperature difference should not exceed 3 °C at the point of the passage. However, the change in heat transfer at the point of contact of the cable with the transformer in comparison to the free-hanging cable between the transformers is partly involved in the uncertainty of the result. The increase of cable heating is also caused by the actual heat losses of the transformers.

The homogeneity of the core temperature at the individual measured points around cable loop is up to 5 °C with a sufficiently precise design of the measuring workplace and regulation system. Significantly increased cable core temperature has a point of connection of the two cable ends. The cable screen and parts of the semiconductive screen insulation are removed from 1 to 2 m of tested cable depending on the test voltage to eliminate the influence of this connection on the measured part of the cable. The cable copper screen is always connected to the earth potential only at one of the ends of the tested cable; otherwise it would also participate in the heating.

2.2. Passive heating methods

Passive methods are based on the generation of heat outside the heated object – MV or HV cable. The heat medium is gaseous or liquid. The hot air chambers use heated air, the liquid containers are the second option. The most common heat medium is water. Its disadvantage is, however, high evaporation, especially at temperatures close to 100 °C. In some cases, this leads to replacing water with oil. Salt water is also used, especially for combined withstand voltage tests with permanent immersion. In practice, various climate chambers or climatic tanks filled with liquid are used the most. The main advantage of these methods is always the galvanic separation of the heating system from the potential of the test sources. Another advantage is the excellent uniformity of cable heating in case of good preparation and sufficient space inside the chamber. Compared to the active systems, the cost of these systems is not high. However, passive systems have large space requirements and they are aggressive to the environment due to evaporation. The practical limitations for cyclic tests are mainly based on the duration of the heating up to the steady state of the heat transfer medium and the heated cable core. The heating time needed to reach 95 °C with stabilization to 1 °C is about 3 hours when using an actively circulating air chamber. Stable heating of the cable in the preheated water bath is about 30 min to 1 hour. The disadvantage is the limited internal space of the chambers. Cable samples have a limited winding diameter - single core 120 mm^2 Al XLPE cable is about 950 mm and identical cable 400 mm^2 approx. 2,400 mm [4].

A specific method of heating is not prescribed by a standard or any directive. However, there is a major difference between active and passive methods, which can significantly affect the results of withstand voltage test or the diagnostic parameters obtained. The generation of heat in the cable by the current passage is, according to the logic, more realistic. Therefore, active cable heating simulations are more consistent with practical measurements.

3. Direct and indirect measurement of cable core temperature

Various cable heating principles have been summarized in the previous chapters. However, the correct determination of the core temperature of the heated cable and its distribution over the entire length is the alpha and omega of the heating system accuracy. There are several basic approaches for determining the temperature, which can be divided into the category of passive - indirect and the category of active - direct. The aim of the indirect method is to determine the core temperature of the cable without direct contact measurement, which would damage the integrity of the cable and its electrical strength. Such cable destruction would make it impossible to perform combined withstand voltage tests with the necessary galvanic isolation of the heating circuit, the temperature measurement system and the high voltage test source circuit. Due to the need to use this measurement method in measurements applied in our infrastructure, a more detailed description will be given in the following chapters.

The direct temperature measurement method is based on contact measurement of the cable core temperature. The temperature is measured by inserting several thermocouples, resistance or semiconductor sensors into pre-prepared cable openings with a depth of about 3 mm deeper than the cable core end position. An alternative is to measure the temperature by contacting the cable ends without insulation. However, there is a different heat transfer to the surroundings and additional heating at the point of connection of the cable ends in case of active induction heating. Active cable heating causes different potentials at different points of connection to the cable core. The temperature measurement system must be able to works with different potentials on individual thermocouples or use isolated sensors to measure the temperature during heating. Overall, the direct temperature measurement method for cable heating can be rejected in our conditions because any damage to the insulation results in an irreversible change in electrical strength in withstand tests as well as in the results of applied diagnostics.

Two other alternative direct methods are practically used. However, their use is time consuming and additionally requires two identical cables for testing. The cable core is heated by the flowing current while the core temperature is determined by direct measurement at several points. The aim of the method is to determine the current value to achieve the required core temperature and the heating time to stabilize the temperature. The second cable is then heated under the same conditions. Then the necessary withstand tests and diagnostics are applied. The principle of the second method is based on simultaneous heating of two identical cables. One cable is used to measure the temperature and its distribution. The withstand tests or diagnostics are applied to the second cable. This principle is used, for example, by the Haefely Hipotronics system “Heat Cycle Test Set” [8] or China version [9]. However, this principle has a number of disadvantages. Double the amount of test cable is needed for carrying out the heating. The test is therefore very demanding on the required testing room space. The heating system input power must be doubled. Practical measurements have shown lower heating homogeneity over the length of the heated cables due to inconsistent heat transfer to the environment. The value of heat sharing is complicated by quantification and possible correction - especially in places of tight joint passage of two cables through toroidal transformer.

Indirect temperature measurement is applied to passive heating methods. The temperature of the cable core and the hot water medium can be considered identical after the stabilization time. The last option - the application of indirect measurement for active cable heating methods is based on the measurement of the change in electrical parameters of the heated samples. This method is complicated, but practical measurements have shown sufficient accuracy as required. A more detailed analysis of this method is described in the following chapters.

4. Automatic measurement of parameters and thermostatic temperature adjustment

Automation system simplifies operation of heating cables and greatly helps to accelerate reaching the set temperature of the cable core and its stabilization. The system of heating cables without automatics is based on the control of heating power by the inverter or autotransformers. The supply voltage of the active heating elements is regulated by the system. However, the electrical parameters of the heated cable vary with increasing temperature. Therefore, the first goal of the automation is to achieve a constant current value for heating the cables. During heating, there is a significant change in the resistance of the cables as well as in the transition resistances at the point of connection of the cable ends. The result is a drop in power when the temperature rises in the case of stabilizing only the input voltage. Constant and thermostatically controlled core temperature is the goal of the next degree of automation. Cyclic cable heating is the most demanding application. PID controllers are used by automatic temperature control systems to achieve the fastest possible heating and temperature stabilization within the required limits. Proportional, differential and integration constants are based on ANSYS software simulations and practically measured values in laboratory tests of automation systems.

Fig.2. Open chamber for passive cable heating

5. Design and implementation of laboratory experiments for cable heating

Several separate cable heating systems have already been developed in CVVOZEPowerLab Infrastructures. The first system is a climate chamber for passive heating of MV and HV cables up to a maximum temperature of approx. 120 °C. Cable parameters were limited by the box dimensions of about 1.2 x 1.2 m, so the maximum usable core cross section of a single core cable is 240 mm^2. The heating is carried out with hot air with active flow and a maximum output of 2.2 kW. The temperature is thermostatically controlled with a hysteresis of approx. 5 °C.

The cable temperature of 95 °C is reached in about 60 minutes with a temperature uniformity of 10 °C. The required uniformity of about 2 °C is reached after 180 minutes of heating. This heating system has provided valuable data and experience for the development of more sophisticated heating systems and can now be used alternatively for smaller cross-section cables up to a maximum length of 20 m. The advantage of this system is the complete and safe galvanic separation for performing combined tests and the relatively high accuracy of the achieved temperature with good uniformity. The system image is shown in Figure 2.

Furthermore, an active cable heating system based on a current transformer has been designed, implemented and practically tested. The maximum continuous output current from the system is 2 kA and maximum output voltage is 3 V. The system can be overloaded for short time with an output current of 2.5 kA for accelerated heating of cold cables in the initial heating phase. The test sample was a cable with a core cross section of 150 mm^2 and a length of 20 m. The cable was tested in the arrangement of one or two loops. However, the current passing through the core of the cable was only about 900 A at a maximum voltage of 3 V due to its large reactance. The cable core reached the set temperature of 95 °C, but the heating was very slow and the temperature uniformity was higher than 10 °C. The aim of our further research was to increase the value of the current passing through the cable to speed up the heating.

One of the offered possibilities was the usage of a new split secondary winding of the current transformer with a maximum current of 1 kA and a voltage of 4 V per winding. The transformer output was rectified by two low voltage drop Schottky diodes. Cable reactance already does not cause a voltage drop because of DC current. In this way, it was possible to reach a cable current of 2 kA with a voltage drop of about 2 V, accelerating the heating and achieving higher temperature uniformity (below 5°C). The main disadvantage of this functional cable heating solution up to 240 mm^2 is the low electrical strength of the secondary transformer winding and connected cable core against ground potential to achieve the parameters required for the combined withstands tests. There is only a very small air gap between the secondary winding and the transformer magnetic core. The electrical strength of the gap is about 10 kV after filling with reinforced PE insulation. Efforts to increase the mechanical dimensions of the magnetic circuit and install more robust insulation have led to increased magnetic flux dispersion of the transformer, reduced efficiency, and the required value of output current has not been achieved.

The third cable heating system, which is based on active induction heating, has solved all the disadvantages of the previous two systems. A system with multiple small toroidal transformers for more uniform heating and less magnetic field dispersion has been proposed based on previous knowledge. The limiting factor is the size of the inner hole in the toroidal transformer with a diameter of 90 mm. This dimension corresponds to a single core MV cable with a core cross section of >500 mm^2. The second limiting factor is the maximum current value of 2.5 kA. This value is for continuous heating and 3 kA for short-term heating within 5 minutes. The last parameter is the required voltage. Based on the practical knowledge of the MV cables voltage drop, the required voltage range is from 0.6 to 6 V for core cross sections from 95 to 500 mm^2. The usage of 6 toroidal transformers of 2.4 kVA is the optimal solution. The voltage per one turn of each transformer is 1 V and the primary winding is divided into two parts of 150 V. The saturation of the transformer magnetic circuit occurs at about 190 V. The connection of the individual primary windings of the transformers can be parallel or serial. Overall, the system can be connected to a maximum voltage of 380 V with an induced voltage in the cable of approx. 7.5 V in open-circuit. The photograph of this system is shown in Figure 3.

Fig.3. Induction system for active cable heating

6. Practical experience with indirect cable conductor temperature measurement

Two methods of indirect cable core temperature measurement have been developed in our laboratory. The first method is based on a simple temperature measurement on the surface jacket of a heated cable with three thermocouples. The average value of this temperature is corrected and the core temperature is calculated. The application of this procedure is suitable and fast to achieve the set temperature for repeating cable samples. Unfortunately, it is very complicated and time consuming to determine the exact constants for a different types of heated cables. As a result, the core temperature of the cable is determined with a maximum error of 10 °C. The conversion constant includes correction for absolute atmospheric humidity and ambient air temperature. The corrected temperature value v_{cor} can be determined from the following equation:

(1) $$v_{cor} = v_{3m} \cdot k_T \cdot k_H \,,$$

where: v_{3m} – the mean of three measurements, k_T – temperature correction, k_H – humidity correction.

Furthermore, it is necessary to determine the corrected temperature value of the cable core v_C based on the heat transfer time from the core to the cable surface jacket. In this equation, the relationship is determined by the difference between the observed core temperature v_{C-1}, which is calculated in the previous iteration, and the corrected temperature v_{cor}. The calculation is shown in the equation (2). The calculation is carried out online on the microcontroller system. Calculation of core temperature and heat transfer depending on the value of the flowing current is an alternative with less accurate results:

(2) $$\upsilon_C = \upsilon_{cor} \cdot K_C \cdot e^{-\frac{t}{\tau_C (\upsilon_{C-1} - \upsilon_{cor})}} \,,$$

where: v_C – cable conductor temp. after last iteration, t – time from start of heating, K_C *and* τ_C – the experimentally determined and for each cable different constants.

This temperature calculation procedure can be applied only under constant current conditions flowing through the cable core and constant ambient conditions.

The new automatic core temperature determination procedure with an accuracy of up to 3 °C has been developed due to the complexity and in some cases the lack of precision of the previous method. The principle is based on the measurement of electrical quantities of the power supply system by the wattmeter and subsequent data processing by the microcontroller. The method is universal and suitable for all types of HV and MV cables as well as for different core materials without the need for complicated determination of constants. Power and voltage regulators must be linear. The best solution is to use a regulatory autotransformer. The condition of proper system operation is a sinusoidal current and voltage wave without significant, especially pulse distortion. Simple thyristor or triac switching of input voltage is unsuitable for this purpose.

The Lutron DW-6092 three-phase power analyzer is used to measure active power and other electrical quantities. The analyzer allows communication with the microcontroller via a serial line. The analyzer's active power measurement accuracy is better than 1 % and the AC current measurement is up to 0.5 % in the range of 0 to 2 kA. Currently, a very accurate Hall current shunt is used for current measurement with a measurement accuracy of 0.1 %. The aim of the measurement system is to determine the change in cable conductor resistance. Warming and the resulting core temperature v_C can be calculated from the change in cable conductor material resistivity using the following equation:

(3) $$v_C = v_S + \frac{R_C - R_S}{\alpha_C \cdot R_S} \,,$$

where: v_C – the resulting core temperature, v_S – the core temperature at the beginning of the measurement - "room temperature", which must be accurately measured, R_S – cable core resistance at temperature v_S, the value is automatically determined by the system during the first measurement cycle, α_C - temperature coefficient of cable core material - table value for Al 0.00392 K^{-1} and for Cu 0.00377 K^{-1} [7].

Measuring the required quantities on the primary side of the toroidal transformer to determine the core resistance R_S is very inaccurate. The cause of the big error is the conversion of the quantities to the secondary side of the transformer. The voltage ratio of the transformer is non-linear and is dependent on the primary voltage, current and power factor. Therefore, it was necessary to correct the nonlinearity of the transformer magnetic circuit by measuring the primary and secondary current, the power factor *cos φ* and applying the 5th order correction polynomial. Unfortunately, the correction was not very effective and the resulting resistivity change calculation error was around 5 % (core temperature uncertainty was 20 to 30 °C).

The method of measuring the electrical parameters on the secondary side (on the heating side) is much more accurate. The value of the passing current I and its phase shift is measured by a Rogowski coil or a Hall current shunt. The voltage U in the heating loop and its phase shift must also be measured to calculate the active power P. Unfortunately, voltage measurement is not available in the loop. The cable core must remain electrically isolated. Using a copper tape screen with one-sided grounding is not possible due to the safety reasons when the cable voltage breakdown appears. The solution of this problem is to create a new measuring voltage loop - parallel to the heated cable through all the toroidal transformers. A voltage measuring loop can be realized by multiple turns n to increase the sensitivity of the wattmeter. The cable core resistance value R_S is then determined by the equation:

$$R_S = \frac{P}{I^2} = \frac{\frac{U}{n} \cdot I \cdot \cos\varphi}{I^2} = \frac{U \cdot \cos\varphi}{I \cdot n}, \tag{4}$$

where: P - the active power of the cable measured by the wattmeter, U - the voltage at the measuring voltage loop, n - the number of turns of the voltage loop, I - the current passing through the cable core and $\cos\,\varphi$ is the power factor determined from the phase shift of the voltage to the current.

Software - PowerAnalyzer was created as a simple user interface for communication with the heating system via PC. The only required input data is the ambient temperature (cable temperature at the beginning of the measurement), the number of turns of the voltage loop and the core material with possible correction or own material constant. The PowerAnalyzer printscreen is shown in Figure 4 [10].

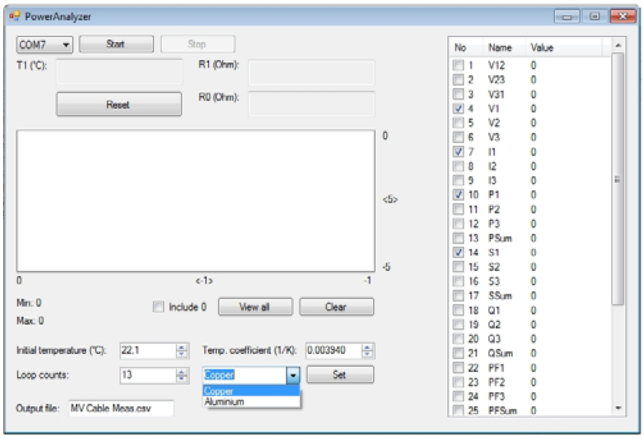

Fig.4. PowerAnalyzer SW user interface example

The PowerAnalyzer software can communicate with a DW-6092 Wattmeter via a serial data line or communicates with a microcomputer that processes data from all sensors and performs online mathematical calculations of the required quantities, including corrections. Figure 5 shows the warming characteristics of the cable obtained by direct and indirect measurement.

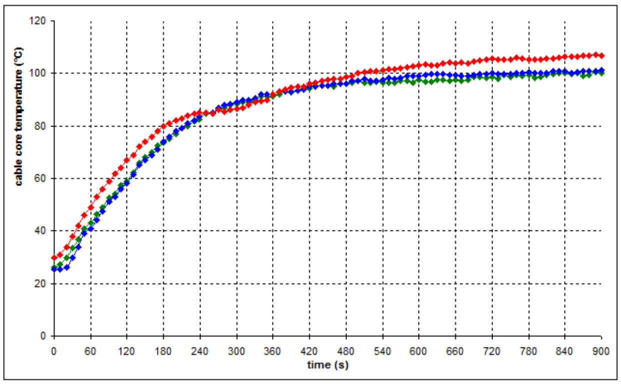

Fig.5. Warming characteristics of 150 mm^2 MV cable by 1 kA current

PowerAnalyzer SW data with no correction is displayed as red curve, the corrected data is green and direct temperature measurement results using a Pt100 temperature sensor with an accuracy of 0.25 °C are blue.

The absolute error of determining the core temperature after correction depending on the resulting temperature is shown in Figure 6. Cable core temperature uncertainty up to 100 °C does not exceed 3 °C.

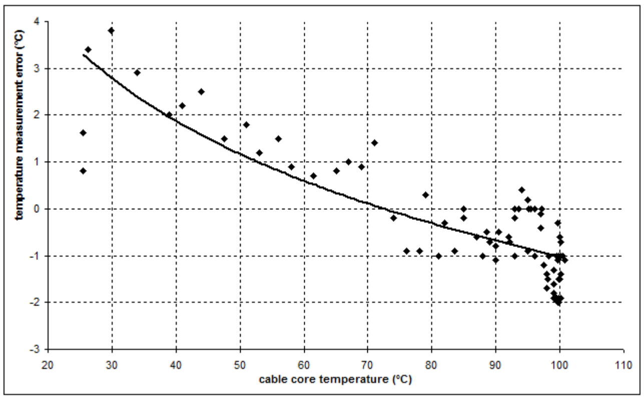

Fig.6. Absolute error in cable core temperature calculation

An autonomous microcontroller-based cable heating system has also been developed in addition to the PowerAnalyzer software mentioned above. The only input is the required temperature, the number of turns of the voltage loop and the core material of the cable. The system itself autonomously regulates the power supply part and regulates the set core temperature with integrated PID controllers. In cycling mode, it can save time significantly. The heating speed of the 150 mm^2 cable core to the temperature of 95 °C takes about 15 minutes and cooling to 40 °C takes about 60 minutes. A photograph of this autonomous system in a compact design is shown in Figure 7.

Fig.7. Autonomous system for heating MV and HV cables

This system has been tested for heating cycling voltage test according to IEC 60840. Cable heating time is 8 hours. The temperature is kept for 2 hours. The cooling is applied for 16 hours. The cycle is repeated 20 times.

Conclusion

The basic principles of cable heating are theoretically described in this paper. Some of these principles have been also tested in the laboratory. The largest part of the practical testing is focused on indirect induction heating, which allows a rapid and uniform heating of cables. The induction heating system consists of six toroidal transformers that can be separately positioned along the length of the heated cable to increase heating uniformity. The greatest benefit of the article is in the new principle of measuring and regulating the temperature of the cable core. Most commercial heating system products use direct measurement methods that damage cable integrity or reduce the electrical strength of cable insulation. Alternatively, a principle of heating two identical cables is used. One is tested and the other is measured for temperature. However, our system requires only one cable for testing and simultaneously the core temperature is measured. A MV XLPE cable of 150 mm^2 was practically tested. The core temperature of the cable was measured both indirectly and directly by using precision Pt100 sensors. The temperature error was up to 3 °C in the range of 20 to 100 °C. These measurements confirmed the suitability of this system for combined cables withstand voltage tests requiring cable conductor temperature accuracy of 5 °C. The automatic cable temperature control system and cyclic climate test system are currently being developed and expanded in our infrastructure CVVOZEPowerlab laboratory.

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