RETURN VOLTAGE – AS A DIAGNOSTIC TOOL FOR HIGH VOLTAGE EQUIPMENT

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Abstract: The phenomenon of return voltage as an idea to diagnose of high voltage equipment has been arisen in mid '60s by the work of Endre Németh [1,2]. On the basis of the measurement of return voltage, two diagnostic methods have been developed: the voltage response (VR), which measures decay and return voltage and the recovery voltage measurement (RVM), which examines the long time constant range of polarization spectrum. While, former has used for condition assessment of cable lines, latter has widely applied for determination of moisture content of transformer insulation since '80s in Hungary. This paper summarises the basics of these methods and shows the newest results of application. Advantages and limitations of these methods are emphasized by a short review of application and laboratory examinations, as well.

1 INTRODUCTION

In mid '60s, Endre Németh brought on the idea of measurement of return voltage as a diagnostic technique of the insulation of high voltage equipment. From this idea, two diagnostic methods have been developed, namely the Return Voltage Measurement (RVM) and the Voltage Response (VR) method. These methods are based on the measurement of the decay and the return voltage curves. Timing diagram and parameters, which are potentially evaluated by measurement, can be seen in Fig. 1. The discharge voltage ($V_d(t)$) can be measured after the relatively long duration (100…1000 sec) charging period (t_{ch}) of the insulation after disconnecting of voltage source. The return voltage ($V_r(t)$) can be measured after the short circuit (t_{dch}) on the charged insulation. The initial slopes of both voltage curves (S_d, S_r) and the peak of the return voltage provide information about the dielectric properties (conductivity and polarisation) of the insulation.

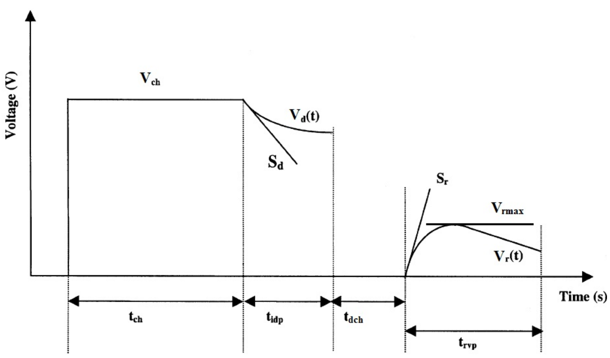

Figure 1: The timing diagram of measurement and evaluated parameters

By measuring of Voltage Response (VR), only the two slopes (S_d and S_r) are evaluated at given charging and discharging times (t_{ch} and t_{dch}). The typical charging and discharging times are 1000 s and few seconds, respectively. Hence, the measurement requires relative short time.

At the measurement of Recovery Voltage Measurement (RVM), the ratio of charging and discharging times (t_{ch} and t_{dch}) is set to 2, and the peak of return voltage is measured. By the RVM, the long time constant polarisation spectrum of the insulation is investigated by the changing of charging time from 0.02 s to 10000 s. Although, this method provides more detailed information about dielectric processes having long time constant, nevertheless the recording of the whole polarisation spectrum requires quite long time. Therefore, precise investigation of polarisation spectrum has used only valuable equipment e.g. power transformers.

2 VOLTAGE RESPONSE MEASUREMENT

By the measurement of voltage response only the gradients of decay and return voltages are evaluated. The initial slope of the decay voltage (S_d) is directly proportional to the conductivity of the insulation. The slope of the return voltage (S_r) is proportional to the intensity of polarization processes. Therefore, from the point of view of information content S_d is equivalent to the I_c conductive component and S_r is equivalent to the I_p polarization component of the leakage current. Using the voltage measurement, the two voltage functions can be measured separately thus the conductive and the polarization processes can be examined separately [1, 2, 3].

2.1 Application on oil-paper insulated cables

The voltage response measurement was developed for oil-paper insulation because the moistening and the ageing (as the two major deterioration processes of oil-paper insulation) can be examined separately by this method. The results of the test easily evaluate by plotting S_d against S_r in log-log diagram (Fig. 2.). The position of the points shows the condition of the insulation. A growing displacement to the right shows an increasing degree of thermal ageing, while a displacement vertically upwards indicates increasing moisture content [2, 3, 4, 5]. In Fig. 2. cable 1 represent a dry, not aged, practically new insulation. The results for cable 4 show an insulation of highly advanced aged state and having rather high moisture content. The conditions of the insulation in the four cables seem to be very different, but the three points representing the core insulation of a cable are very close to each other. The scatter of the points is rather low.

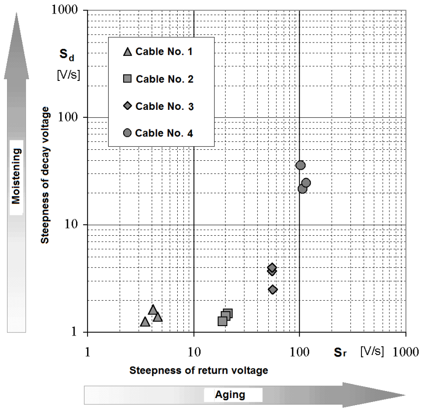

Figure 2: Results of VR measurements on oil paper

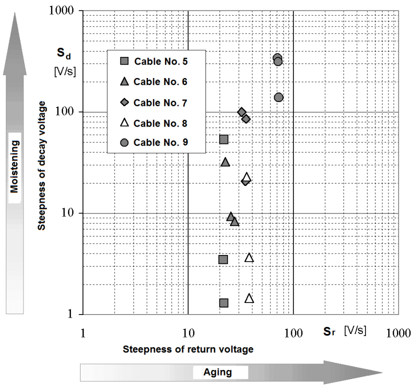

Figure 3: Pattern of VR parameters of aged and moistened cables

In Fig. 2., several characteristic results obtained on cables of rather bad insulation condition are plotted (Cable No. 5-9). Higher steepness of decay voltage at least one core insulation and higher vertical scattering of the three core insulation can be observed. Cables 7 and 8 show a slightly higher degree of thermal aging and high moisture content and broke down after two and seven months the test, respectively. The results of cable 9 show the insulation to be in considerably advanced thermal aging state and extremely high moisture content. However, this cable had not been working for several years before the testing. Consequently, the results of the voltage response measurement predicted the damage of the cables [2, 3, 4].

2.2 Application on PVC insulated cables

The application of voltage response method on PVC insulated cables was investigated on medium and low voltage cables, too. In both cases, parallel chemical tests (thermal stability measurement) were carried out. The thermal stability is a measurement method to determine the amount of the active stabilizer in PVC [5, 6]. At this test, a defined mass of the material is heated to 200 °C and the time necessary up to the appearance of HCl is measured. The typical value of thermal stability is 100-200 minutes on new PVC and the result depends on the manufacturing technology of PVC.

2.2.1 Results of field tests of MV cable lines

Parallel thermal stability and voltage response measurement were performed on 6 kV cable samples [5]. The samples were cut out form the cable net of an industrial plant after 10-12 years of operation. The results can be seen on Fig. 3.

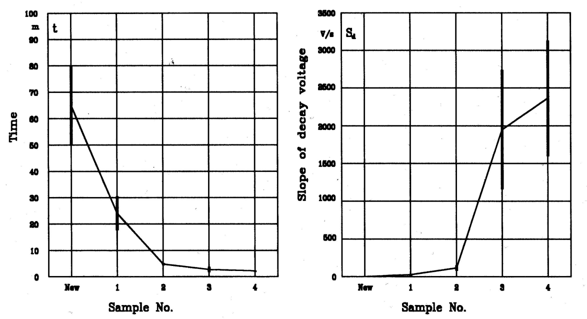

Figure 4: Relationship between the thermal stability and the decay voltage [5]

By the comparison of curves of Fig 3., an inverse ratio can be observed between the thermal stability and the specific conductivity of the PVC insulation. It means that the chemical degradation of the cables can be examined by non-destructive electrical methods, by measuring its dielectric parameter, namely the slope of the decay voltage.

2.2.2 Results of laboratory aged LV cables

Thermal aged cable samples were tested by the voltage response method. Specimens having 0.5 m length were cut out from a multicore PVC insulated low voltage control cable [6]. At the investigation, each core of a cable sample was measured in order to find the most significant one, which should be measured on-site. In this paper, only the results of most significant core are presented. The tested cable is operated in a tempered hall where the ambient temperature is constant 35 °C and other stresses e.g. moisture, radiation and temperature changing are neglected, accordingly thermal aging is used in laboratory. The degree of thermal aging is determined by the using of the well-known Arrhenius-equation:

$$t_a=365t_s/\exp(E_A/K_B(1/T_s-1/T_A) \qquad (1)$$

where t_a is the accelerated aging time in days, t_s is time in service in years E_A is the activation energy in eV, K_B is the Bolzmann constant, T_S is the operating temperature T_A is the temperature of the accelerated aging expressed in °C. In the examination 0.8 eV activation energy is assumed for the deterioration process of PVC insulation. By this equation, the time of accelerated laboratory aging can be converted into equivalent time in service. The result of the thermal stability measurement can be seen in Fig. 4. The stabilizer content of the sheath is higher than that of core insulation but the decreasing of this parameter in both cases is near parallel. The falling of the breakdown voltage is started when the thermal stability about 15 minutes.

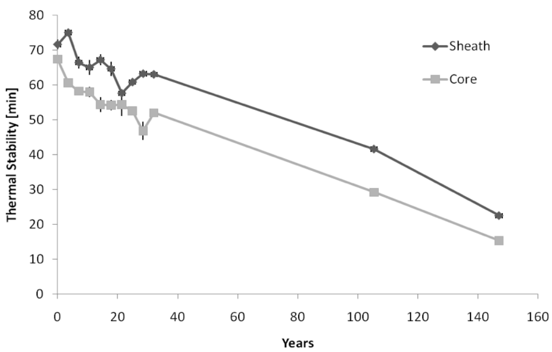

Figure 5: Thermal stability of the sheath and the core insulation [5]

The results of voltage response measurement can be seen in Fig. 5. The horizontal axis represents the equivalent years in service, while the steepness of the decay voltage is on the vertical axis. The diagram shows that the steepness of decay voltage increases gradually by the equivalent years in service. The result makes this parameter suitable for determination of the thermal aging of PVC cables. Especially, the measurement of this parameter is capable for on-site and non-destructive testing [5]. The steepness of return voltage does not provide useful information about the ageing of PVC insulation [5,6], while this parameter of oil-paper cables is proportional to thermal aging.

These results have enabled this method to diagnose low voltage public lighting cables. The condition monitoring of these cables has become more important because the replacement of whole cable networks is not a cost effective asset management strategy. By the results of this diagnostic method, the most degraded cable lines have been ranked and the replacement strategy can be determined [7].

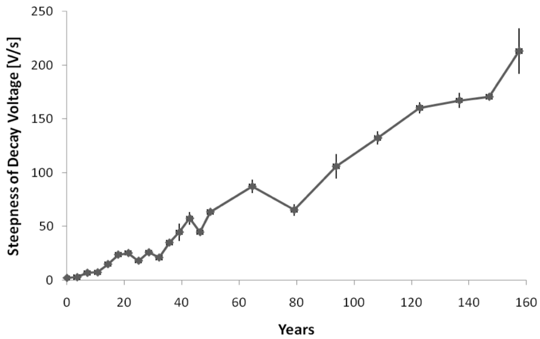

Figure 5: Voltage response measurement on laboratory aged PVC cables [5]

3 RECOVERY VOLTAGE MEASUREMENT

At the Technical University of Budapest, in the mid of 1970's, Prof. András Csernathony-Hoffer, the Hungarian regular member of CIGRE SC 15, has recognized that the investigation of "long time polarisation phenomenon" would be a promising tool for condition assessment of insulations. Therefore, he led an investigation to find a simple and easy method for the determination of the "time constant-long time polarization" function, with other words, of the spectrum of the long time polarisation phenomena, and the use of this for the diagnosis of the insulation systems. As a result, a new diagnostic method was developed for oil-paper insulating systems (transformer and cable) with the determination of the polarization vs. time constant curve shape, by a series of return voltage measurements. The internationally accepted name of this method is RVM method, created from the words Recovery (or return relaxation) Voltage Measurement method.

3.1 Short review of the RVM method

Substantial in the method is, that it uses to the determination of the spectra DC charging voltages, end DC voltage measurements. This type of measurements is not sensitive for interferences; this can be made reliably on site, even in the highest voltage transformer stations, in noisy environments. By this developed method, the measurements were made as follows: to the electrodes of the tested equipment a V_{ch} charging voltage is given, for a t_{ch} charging time. In consequence, all polarization phenomena with a time constant smaller than, or equal to t_{ch} will be more or less activated. After elapsing of the t_{ch} charging time, with short-circuiting the electrodes, a discharging takes place for the t_{dch} discharging time. As a result, all polarization phenomena, activated during the charging, will be more or less deactivated, when their time constants are smaller than the t_{dch} discharging time. After elapsing of this discharging time, the short-circuiting is ended, and so the - during the charging - activated, and - during the discharging - not deactivated polarization develops a relaxation (recovery, or returning) voltage on the electrodes. The V_{rmax} crest value of this relaxation voltage is measured. The time diagram of this measuring process is shown in the Fig.1. If the t_{ch} charging time, and the t_{dch} discharging time is varied in the manner, that their quotient stays constant (for example t_{ch}/t_{dch} = 2), and the measuring procedure is repeated - as described above - with a series different (in each step increased) charging times, started with e.g. 0.02 s, and ended with e.g. 10 000 s, than we get some kind of polarization spectrum, in this time constant interval, the curve shape of which characterizes in some way the state of the insulation.

3.2 Application on oil-paper insulation system

Fig.6. shows curves, drawn with this method, measured on oil-paper insulation system models, with exactly present the paper humidity content, and the temperature. During the development and testing works, and afterward, during more than ten years of great transformer diagnostic measurements, and also some years of cable diagnostic measurements at the electrical power system of the Hungarian Electricity Board, it was proofed, that this method is very useful to the practice. The results got by this method are independent of the dimension, of the shape, of the oil-paper proportion, of strange or local effects, as e.g. dirty bushings, or the shunt resistance and capacity of the measuring equipment. It was proved too, that beside the general state, inhomogeneities of some extension also can be detected with this method.

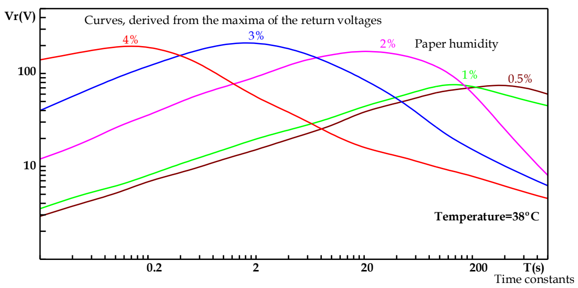

Figure 6: Typical RVM spectrums of oil-paper insulation with different humidity content

3.3 Influence of local defect on RVM spectra

The RVM method is not sensitive to local defects, or effects that decrease the insulation resistance, or increase the capacity, for example to a wet, or dirty bushing, or end sealing insulator, or a defect cable joint, which decrease the insulation resistance [9]. Fig.7. shows a series of measurements on a "three time constant model", made in under the same conditions, but with different the insulation resistance decreasing shunt resistors. Vhe values of these were respectively 1 GΩ, 100 MΩ and 22 MΩ. It is clear, that in spite of the decreasing of the absolute values of the relaxation voltage maxima with the decreasing the resistance, the shape of the curves, and so the places of the crests, and with them the determinable dominant time constants stayed the same.

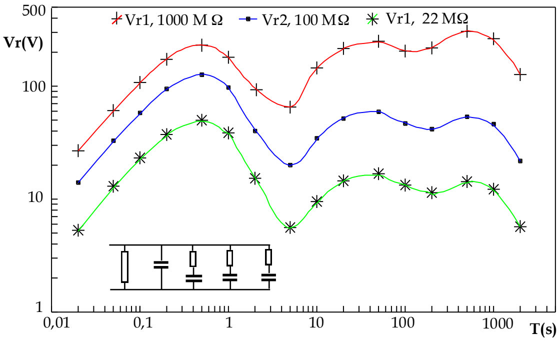

Figure 7: Effect of shunt resistance on RVM spectrum

3.4 Temperature dependence of RVM spectrum

As generally all dielectric parameters, the polarization spectrum is also temperature dependent: dependence is shown in Fig. 8. (and can be seen clearly in Fig. 9. too). The differences, caused by the different measuring temperatures, can be taken into consideration, if the temperature of the insulating paper is — at the time of the measurements — known. As it can be seen, these curves have generally one dominant maximum. The charging time, related to this maximum can be called "dominant charging time" and this dominant charging time can be regarded, with a good approach, as equal to the "dominant time constant" of the polarization. Further, this dominant time constant is an unambiguous function of the general state, and the temperature of the paper component of the oil-paper insulating systems.

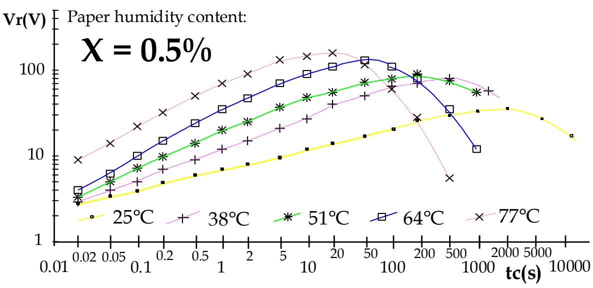

Figure 8: Temperature dependence of RVM spectrum

3.5 Computer aided interpretation of RVM

The base of the analyzing is that “nomograms”, what are shown in the Fig. 9. It measured [10] in the 1980s in the High Voltage Laboratory in

Budapest University of Technology and Economics.

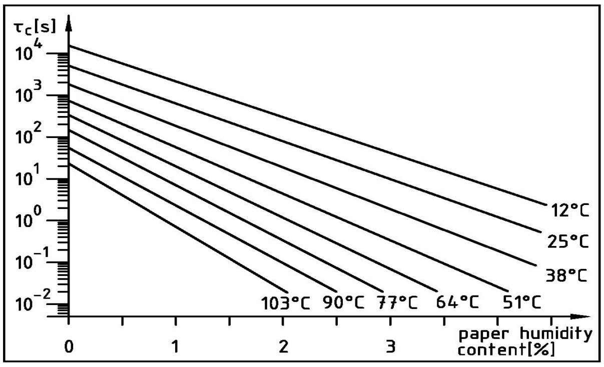

Figure 9: RVM "nomograms" enabling evaluations of RVM "spectra"

The "nomograms" are shown the dominant time constant in the function of the moisture content. Sometimes, these curves could give rise to misunderstanding that reason it is to be again noted the followings. In this case the insulation system gets new oil, new paper, the temperature distribution is homogenous, the polarization spectrum gets a single time constant which is in unambiguous relation with the moisture content of the paper. If the insulation system is not homogenous, we have to use the whole spectrum to characterize the condition if you are in possession of such of reference data. Now we would like to demonstrate the fundamental phenomena, therefore the interpretation is easy. Otherwise, the interpretation is complicated but it is possible if we possess the above mentioned reference curves. In our case the parameter is the temperature. So in the course of the evaluating the different temperature values are very important factors. For example the moisture content at τ_c=10s and T=90°C is X=0.6% but with the same time constant gives X=3,3 % moisture content in T=20°C. It is very important differential, according to older RVM results what measured on a failed transformers the 3,5% moisture content is dangerous. The temperature cannot be eliminated in the course of the evaluating! So it is very important to calculate with the temperature and moisture content, too!

Our new computer aided evaluating method use an exact values for the temperature and moisture content, too. It is precise if the evaluation made with an analytic method [11]. The equation form is shown below.

$$\tau(X,T) = k'\times 10^{-m'\times T}\times 10^{-k''\times 10^{m''\times T}\times X} \qquad (2)$$

Where *τ(X, T)* is the measured dominant time constant in the function of the moisture content, the temperature and some constant parameters (k',m',k",m"). In a view of the measured data (temperature and the dominant time constant) the moisture content can be calculated. To calculate with the inverse form of this equation is very difficult, so it practical to make this evaluation on a computer. It provides a lot useful possibility way to complete the evaluation. It provides also to make a comparison of two RVM diagram on a variant temperature if the diagrams shifted to the new calculated τ_c'. The new τ_c' can be calculated with the (2) equation if the moisture content is constant. The original and the shifted diagrams are shown below on the Fig. 10. The new RVM diagram gives some important information about the behavior of the insulation. For example if the recovery voltage is bigger than some level, increases the loss in the insulation, which can cause fault. This problem is relevant especially where the excitation is continuous (50Hz).

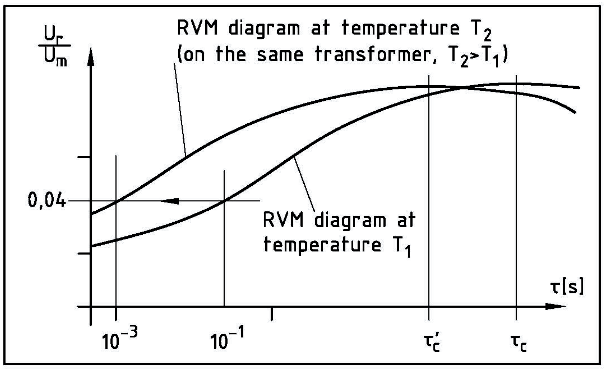

Figure 10: RVM diagrams at different temperatures

3.6 Application on cable line with two sections

All effects and the results gained from the Return Voltage Technique can be easiest explained if we represent the behaviour of a dielectric by an equivalent circuit, shown in Fig. 11.

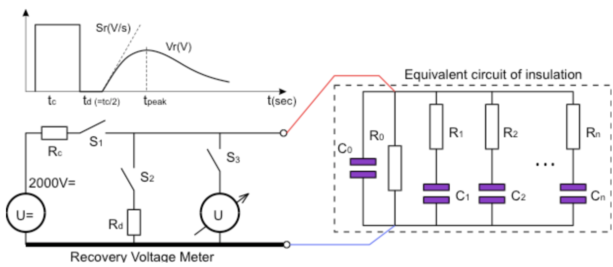

Figure 11: RVM measurement cycle and equivalent circuit

On a quite old cable there were rather frequently faults. It must be decided, whether it is worth to repair it, or it would be better to change it for a new one. This cable branch contains two sections. To support the decision an RVM measurement was made, with the results shown in Fig. 12. It can be clearly seen, that one section of the cable branch was in bad condition (time constant very low, below 1 s), but the other section was in medium condition (time constant app. 10 s). If we use the single voltage response technique, it is more complicated to know that the two section of the cable branch is different condition and we have to change only one section. The decision can be made if the dielectric parameters of sections are quite different e.g. one section is oil-paper and the other one is XLPE insulated [12]. We can realise that the RVM technique is applicable to show the inhomogeneous condition in that case when both sections have same insulating material. In our case the cable section in bad condition was changed and with the new section the cable branch is in service up to now.

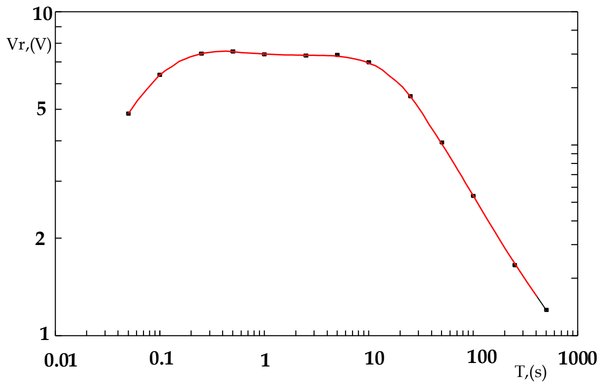

Figure 12: RVM spectrum of a cable line of two aged 10 kV cable in series

4 CONCLUSION

The diagnostic methods (voltage response and return voltage measurement), which have been developed based on the phenomena of return voltage, are widely used for condition assessment of equipment having oil-paper insulation in Hungary. Many experiences have been collected since these introduction and many research works have been proven the usefulness and reliability of these methods. This paper summarises the knowledge about the application of diagnostic methods based on return voltage and introduces the newest results of research works of this field.

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