Recovery Voltage Measurements of Oil-immersed Transformer

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One of the methods currently being investigated as a possible non-intrusive diagnostic tool for condition monitoring of power transformer and cable is the recovery voltage measurement, which will be improving the ability to detect the content of water concentration and the ageing process in the insulation system and may thus be an indicator of insulation quality and its ageing status. The polarization phenomenon was studied using RVM with oil-paper samples. In order to interpret its mechanism, the Extended Debye model was introduced. With different circuit parameters, various simulation results were gotten. Furthermore, with the test samples of different ageing condition, measurements are accomplished in the lab. On the basis of this experiment as well as theoretical analysis, correlations between polarizations and ageing were analyzed.

Keywords : Recovery voltage measurement, Oil-paper insulation, Ageing, Power transformer

1. INTRODUCTION

Economically reliable and effective power delivery is always the primary concern to utilities all over the world. Insulation diagnostics is one of the requirements for safe operation of high voltage apparatus. Conventional methods for on-site assessment of insulation condition are based on loss factor, insulation resistance and partial discharge measurement, and so on. These methods, however, provide only partial picture about the polarization processes within insulating material. The open power market has increased the competition and also emphasized on the search for the new, efficient and effective methods for diagnosing the insulating system. The use of the Recovery Voltage Measurement (RVM) may be a significant way to detect the insulation ageing of operating power transformer in a non-destructive manner[1]. RVM is less noise-sensitive and is simple to set up on-site. The main drawbacks are that the curve is sensitive to the leakage current due to input impedance of measuring voltmeter, polluted terminations, splices, and the length and electrical characteristics of the connecting cables. But till now, the interpretation of the measured data of RVM is difficult as the measured dielectric response contains much information pertaining to the interfacial and dipolar relaxation mechanism. The main objective of this study is to develop the relationship between RVM and ageing condition of oil-paper insulation system. The aim is to investigate the relaxation response. To characterize the response, the Extended Debye (ED) model was employed for the theoretical simulation[2,3]. Furthermore, with the test samples of different accelerated ageing condition, measurements were accomplished in the lab. Interpretation of these measurement results and the comparability of these procedures were discussed also.

2. BASIC THEORY OF DIELECTRIC RELAXATION

When a dielectric material is polarized with electric field $E(t)$, the charges induced at the electrodes are given by the sum of the instantaneous free space contribution and the delayed dielectric polarization $P(t)$ as

$$D(t) = \varepsilon_0 E(t) + P(t) \quad (1)$$

In general, the observed polarization $P(t)$ contains two parts[4]:

$$P(t) = P_{rapid}(t) + P_{slow}(t) \quad (2)$$

To predict this polarization behavior, the dielectric

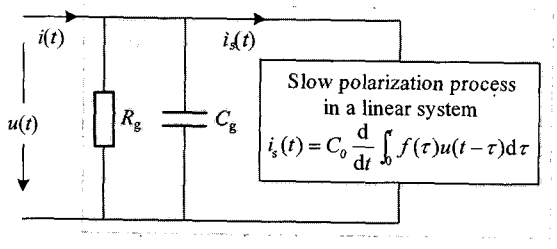

Fig. 1. The model of linear dielectric material.

response function $f(t)$ of the dielectric medium to specified electrical perturbation would be evaluated by

$$f(t) \equiv 0 \quad \forall t < 0 \quad \text{and} \quad \lim_{t \to \infty} f(t) = 0 \tag{3}$$

The slow polarization process can be defined as the sum of delta-function perturbation of strength $E(t)dt$:

$$P_{\text{slow}}(t) = \varepsilon_0 \int_0 f(\tau)E(t-\tau)d\tau \tag{4}$$

The rapid polarization process can be combined with the first term on the right side of equation (1) and can be rewritten as

$$\varepsilon_0\varepsilon_r E(t) = P_{\text{rapid}}(t) + \varepsilon_0 E(t) \tag{5}$$

where ε_r is the relative dielectric permittivity at power frequency.

So using the assumptions in equations (2), (4) and (5), the current density through the dielectric medium can be derived from equation (1) after substitution:

$$j(t) = \delta E(t) + \varepsilon_0\varepsilon_r \frac{dE(t)}{dt} + \varepsilon_0 \frac{d}{dt} \int_0 f(t-\tau)E(\tau)d\tau \tag{6}$$

If the dielectric material is considered as a homogenous one, equation (6) can be rewritten in terms of equivalent lumped parameters as

$$i(t) = \frac{u(t)}{R_g} + \frac{d}{dt}\left\{C_g u(t) + C_0 \int_0 f(\tau)u(t-\tau)d\tau\right\} \tag{7}$$

where $i(t)$ is the polarization current of the dielectric material, $u(t)$ is the applied voltage across the materials, R_g represents the equivalent leakage insulation resistance, C_g represents the equivalent shunt insulation capacitance at power frequency, and C_0 represents the equivalent geometrical capacitance in free space. And the model of such material is shown in Fig. 1.

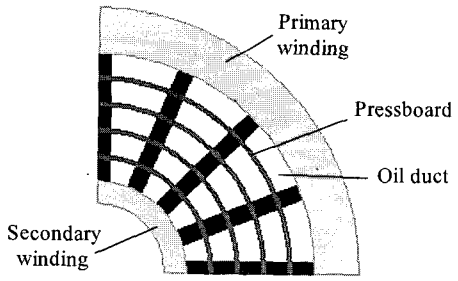

Fig. 2. Insulation system structure of power transformer.

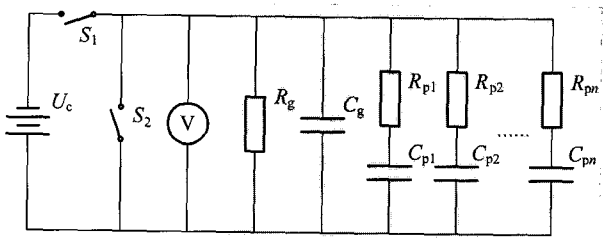

Fig. 3. Equivalent lumped circuit.

3. ESTABLISHMENT AND SIMULATION OF EQUIVALENT MODEL

3.1 The construction of oil-paper insulation

The insulation system of power transformer is oil immersed paper and pressboard, and its typical structure is shown in Fig. 2. Between primary winding and secondary winding, paper barriers and oil ducts in serial are composed of the insulation system. To simulate the polarization process, the simplified lumped circuit during the RVM test is developed as shown in Fig. 3[5].

3.2. Simple circuit parameter

In this investigation, the circuit with a pair of relaxation elements is studied, as shown in Fig. 4. The relationship between circuit parameter and RVM is analyzed at first.

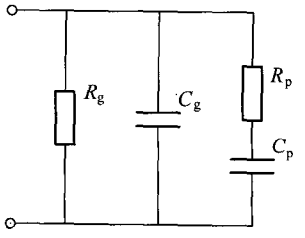

Fig. 4. Simple equivalent circuit.

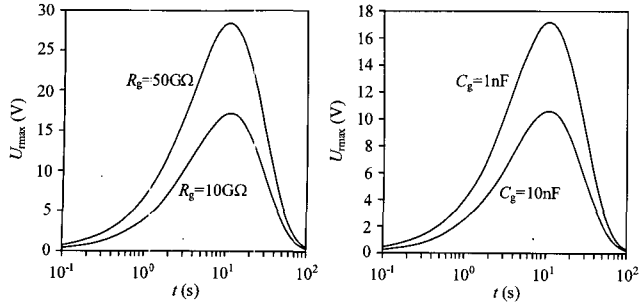

Fig. 5. Simulation with different R_g and C_g.

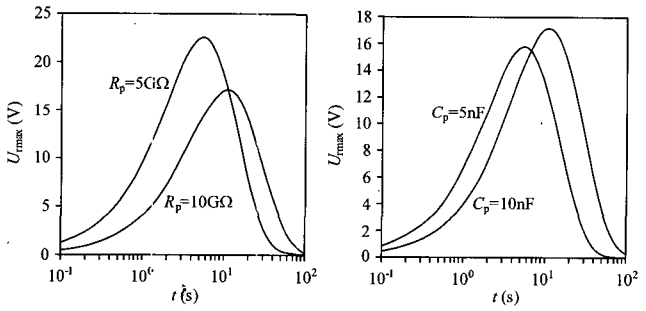

Fig. 6. Simulation with different R_p and C_p.

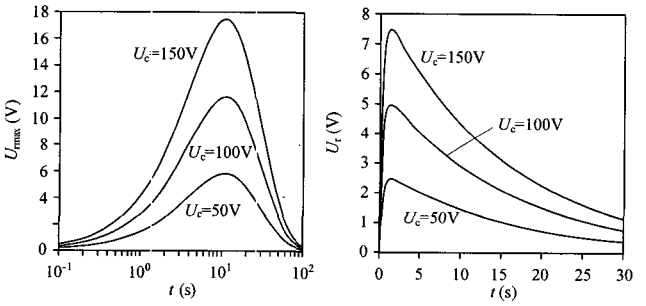

Fig. 7. Spectrum and RVM curve with different U_c.

The value of R_g or C_g in Fig. 4 is changed individually, and the comparisons of RVM measured are shown in Fig. 5. From the simulation results, we can find that if the U_c is fixed, smaller R_g will enhance the polarization current, and higher C_g will enhance the polarization energy, therefore the peak value of the curve will decrease in this condition.

Next, the value of R_p or C_p is also changed individually, and the comparisons of RVM are shown in Fig. 6. From the simulation results, we can find that if the U_c is fixed, different values of R_p and C_p will change the relaxation time, so the time to get the peak will also change correspondingly.

The RVM under different U_c is also studied, and the simulation result is shown as Fig. 7.

When the ageing or moisture fault occurred in the insulation system, these four parameters will change.

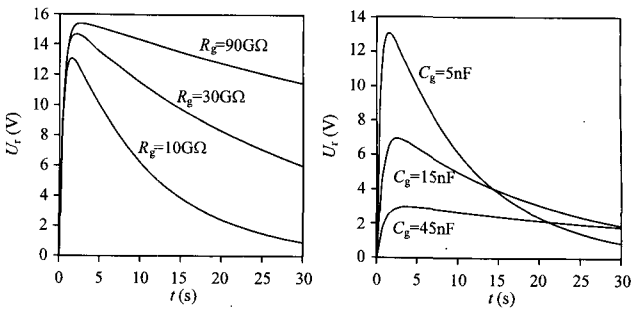

Fig. 8. Simulation of ageing or moisture condition.

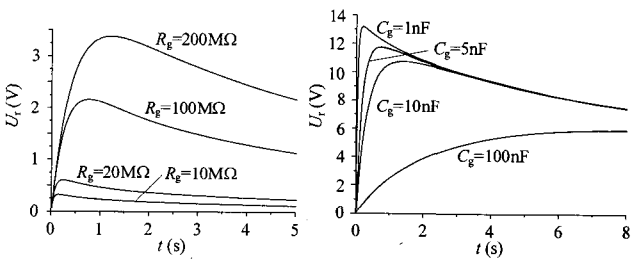

Fig. 9. Comparison RVM with different R_g and C_g.

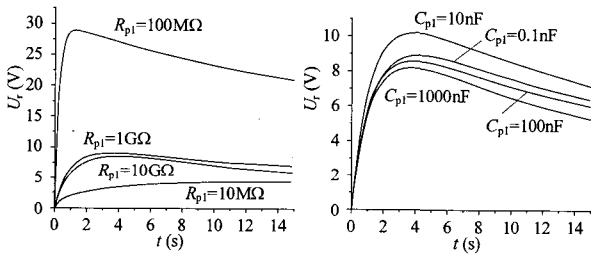

Fig. 10. Comparison RVM with different R_{p1} and C_{p1}.

Some related simulation results are shown in Fig. 8. According to simulation, it can be concluded that R_g mainly affects the peak amplitude and C_g affect the peak and the shape of the curve.

3.3 Complex circuit parameters

In fact, the polarization process during insulation system ageing is very complex. More than one kind of polarization process will be changed during the transformer insulation system was aged or moistened. The aforementioned simulations consider only one kind of polarization. Besides the simple equivalent circuit as shown in Fig. 4, the complex circuit also is considered. In this investigation, the model with 7 pairs of relaxation elements is established, as shown in Fig. 3. Similar to simple model, the effect of different circuit parameter is studied. Fig. 9 shows the results of different R_g and C_g. And the similar phenomenon with that of simple circuit can be found.

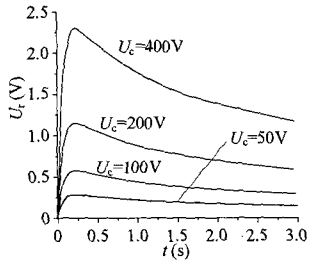

Fig. 11. Simulation RVM with different U_c.

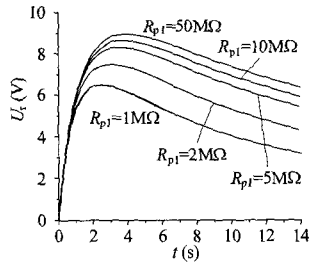

Fig. 12. Simulation RVM with same τ.

Among multi-relaxation elements, we consider the pair for acting the main effect. For short, the parameter of first relaxation element is studied. Fig. 10 shows the simulations with different the R_{p1} and C_{p1} in Fig. 3. As in the multi-relaxation case the results compared with the simple circuit case, we find RVM has some different characteristics. With R_{p1} decrease, RVM will not changes a lot until R_{p1} lower than some value, and then RVM will enhance greatly. If R_{p1} is still lower, RVM will fall a lot. On the contrary, with the increase of C_{p1}, the curve of RVM will rise, and then fall.

Figure 11 shows the simulation under different U_c. The RVM tendency is still similar to the same condition aforementioned.

Figure 12 shows the simulation with the same time constant τ. With the increase of R_{p1}, the RVM curve will rise. Although the τ is fixed, the time to peak value will prolong.

4. EXPERIMENT AND RESULTS

4.1 The guideline of RVM and the definitions of its parameters

Based on the relaxation phenomenon, the principle of RVM test is shown in Fig. 13. First, the sample is charged

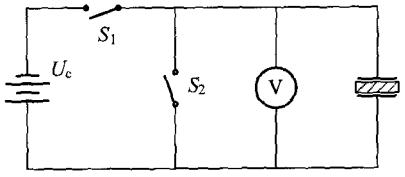

Fig. 13. Circuit connection of RVM.

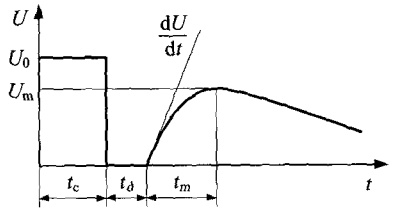

Fig. 14. Principle of RVM.

with a DC source for a charging time t_c. Then, the sample is disconnected from the source and short-circuited for a discharging time t_d. At the end of time t_d, short-circuit is removed and a rather low recovery voltage will appear between the electrodes that might be measured. Three main characteristic parameters of the recovery voltage curve can be defined as shown in Fig. 14: 1) the maximum value of recovery voltage, U_m, 2) the time to the maximum voltage, t_m, and 3) the initial increase rate of recovery voltage, dU/dt. By varying charging time t_c and discharging time t_d, a series of measurements can be performed. As an example, the value of U_m, t_m and dU/dt as obtained for each measurement can then be plotted versus charging time t_c as the polarization spectra. Although the influencing factors for the RVM curves are not clear enough, the poor insulation will generally have larger U_m.

The RVM test may easily be applied to different types of HV apparatus and have already been successfully used for diagnostics of power transformers, as it is suitable for the evaluation of general status of oil-paper insulation system. In fact, the equipment for RVM test is also more compact than that of loss factor measurement.

4.2 Preparations of test samples

According to the IEC354, the accelerated ageing process of some samples of paper and pressboard is carried

Table 1. Ageing parameters and equivalent operation time for tested samples.

No.	A0, B0	A1, B1	A2, B2	A3, B3	A4, B4	A5, B5
Ageing temperature (°C)	/	170	170	170	170	170
Ageing time (h)	0	24	48	72	96	120
Equivalent operation time (a)	0	10	20	30	40	50

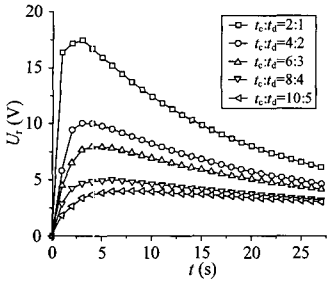

Fig. 15. Comparison RVM with different t_c and t_d.

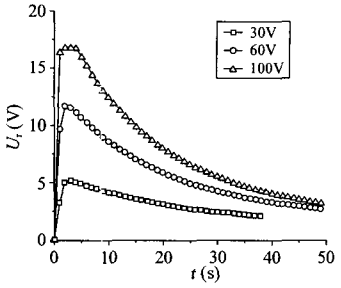

Fig. 16. Comparison RVM under different U_c.

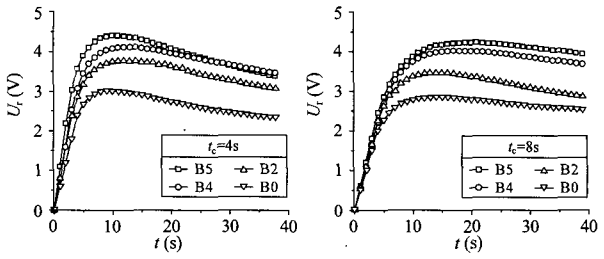

Fig. 17. Comparison RVM with different t_c.

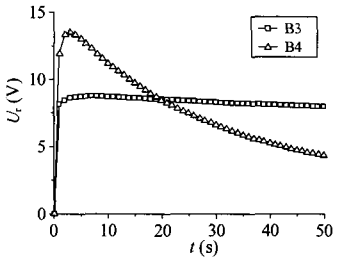

Fig. 18. Comparison RVM with different ageing conditions.

on in the lab. The corresponding ageing temperature, ageing time and the equivalent operation time is listed in Table 1, where A represents the paper, and B represents the pressboard.

4.3 Results of test samples

RVM are accomplished under various test conditions, such as different t_c and t_d, different U_c, different ageing period, etc., as shown in Fig. 15, Fig. 16, Fig. 17, and Fig. 18, respectively.

5. DISCUSSION AND CONCLUSION

The RVM test is a convenient method to test the dielectric response, which reflects the polarization behavior of the insulation and is capable of assessing the condition of oil-paper insulation. The interpretation of the measured RVM results is difficult as the measured dielectric response contains so much information pertaining to the interfacial and dipolar relaxation mechanism. The application of equivalent circuits to characterize the insulation dielectric processes is useful for simulation and measurement as well. Using the derived equation from the ED model and the measured RVM results, the ageing characteristics may be evaluated. All the measured RVM responses show a single peak response, and the RVM response is linear with charging voltage. The ED model parameters may be used to predict three existing ageing indicators: the maximum recovery voltage, the time to the voltage peak and the initial slope. A good correlation between the recovery voltage across the test object produced by relaxation and the ageing process might be established based on the ED model.

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