The Experience in Applying New Recovery Voltage Parameters for the Impregnated Paper Insulation Cable Condition Diagnostics

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ANNOTATION

New diagnostics parameters have been examined for the electric insulation technical condition estimation, which are calculated from the recovery voltage curve. It has demonstrated that their application gives an opportunity to control insulation ageing by both the volume charge condition change, and conductivity change. The experience in using these parameters is contributed for estimation of the technical condition of the impregnated paper insulation power cables after a long-term service in cable premises of nuclear power stations. The experimental results have shown that through the introduction of new parameters recovery voltage becomes a powerful method for controlling electric insulation at early stages of ageing and all the way down for it to achieve a limit state.

KEY WORDS

Electric insulation, recovery voltage, diagnostics parameters, conductivity, volume charge, polarization, cable, impregnated paper insulation.

INTRODUCTION

The recovery voltage (RV) measurement in cable and electrical equipment insulation is used as a method of their technical condition control including the paper impregnated lead cables (PILC). There are two main processes that determine the RV value: volume charge (interlayer) polarization and volume conductivity [1]. This gives reason to believe that control over ageing and moisturizing of the paper electric insulation can be performed by the RV value and form. That said, a wide introduction into practice of this method is restrained due to lack of full understanding of how does one get quantitative data from the RV curve in order to describe insulation ageing and moisturizing, and the effort to extract the input of conductivity and polarization to this curve remained unsuccessful. The task becomes even more difficult due to the dependence of both the RV value and form from the temperature and geometry of the controlled insulation, its type, and the parameters directly forming the RV value and form: charging voltage U_{ch}, charging time t_c and partial preliminary discharging time t_d.

This article presents a new approach towards estimating an electric insulation condition, which allows sharing the input of volume polarization and conductivity gained pursuant to the RV measurement results in the 6 kV PILC with different insulation ageing degree after a long-term service in NPP cable premises. Apart from the RV measurement for the cable condition control there were measurements of insulation resistivity, wide band dielectric dissipation factor, parameters of the partial discharge (PD) at damping oscillating voltage (the OWTS method) conducted, and time-space reflectometry was used.

IDENTIFICATION OF THE DIAGNOSTIC PARAMETERS FROM THE RECOVERY VOLTAGE CURVES

The basis for developing new diagnostic parameters (DP) is the approach for describing the recovery voltage curve $U_r(t)$ based on the traditional fitting, where the real relaxation polymer spectrum is replaced with the discrete set of Debye relaxation oscillator [1]. This allows conducting analysis in terms of the linear electric circuit theory, presenting the complex of the Debye relaxation oscillators as an equivalent electric circuit of the shunted R_iC_i circuits$(i = 1, \dots, n)$. The assessments provided in [1] have shown that relaxation oscillators with characteristic time scales making (0,2 - 50) $\cdot\, t_d$, while the RV maximum is formed through relaxation processes with time scales of about 100 $\cdot\, t_d$ and volume conductivity of an insulation material. For practice the important part is that the reduction of the relaxation processes down to three with constant time scales of about 1, 10 and 100 *s* almost doesn't lose the description precision of $U_r(t)$. Based on the assessments provided in [1] for $U_r(t)$ description one can use a semi-empirical model as a sum of exponents with constant parameters A_i and τ_i

$$U_r(t) = \sum_{i=1}^{n} A_i \cdot exp\left(-\frac{t}{\tau_i}\right), \qquad (1)$$

where t is time. And to describe actually measurable RV curves in the time band of 0,1 – 2000 *s* it would be sufficient for the *n*-value to amount to 3,4 or 5. A typical curve and its components defined by the model (1) are presented in Fig. 1. Here, as is customary, the RV polarity is negative, so the short-lived components are of positive polarity. It seems obvious that parameters A_i and τ_i or the RV maximum U_{rm} and its position in the time scale T_{rm}, may serve as the electric insulation DP, but these parameters depend, firstly, on the geometrical insulation dimensions, and secondly, these indicators don't allow simultaneously conducting a quantitative assessment of both the conductivity change, and the change in insulation polarization properties.

Usually $U_r(t)$ parameters are used for the electrical insulation moisturizing assessment, since it's fundamentally clear that the increase of the conductivity will lead to $U_r(t)$ curve "suppression", i.e. to value reduction and to the shift to the left on the curve time scale $U_r(t)$ [2, 3]. In practice such limited RV use when conducting technical diagnosis may lead to wrong conclusions on the insulation condition. By way of example of such errors, diagnostics of the PILC with typical defect – paper insulation shrinkage can be considered. Such defects are developed in vertical sections of cable routes after a long-term service due to saturant depletion. The development of such defects up to a certain point leads to the $U_r(t)$ curve shift to the right and the increase of its maximum. Thus, the use of the custom diagnostic parameters may lead to wrong conclusions on the PILC condition.

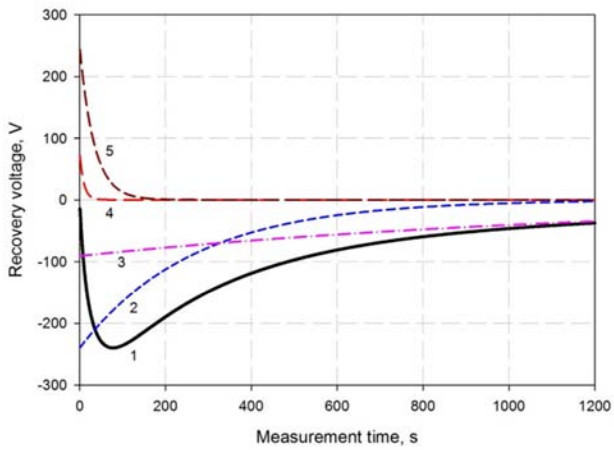


Fig. 1: Typical curve of the recovery voltage (1) and its components (2 – 5)

In works [4, 5] a new approach towards determining the DP from the $U_r(t)$ curve is described. As a rule, the development of the electric insulation defects leads to the occurrence of new or the change in the existing ones in its volume of charge states and the change in conductivity. To control these processes it was suggested to use two indicators: polarization index PIRV on recovery voltage and conductivity index LIRV. Both these condition indicators are calculated from the RV max value.

PIRV is defined as a ratio of the RV maximum U_{rm} to the amount of intensities of the short-lived positive components A_+:

$$PIRV = 10 \cdot |\, U_{rm}/A_+| \tag{2}$$

and the LIRV indicator is defined as a ratio of U_{rm} to the total area of the short-lived component S_+:

$$LIRV = 100 \cdot |U_{rm}/S_+|. \tag{3}$$

In both cases the multiplying factor and the modulus sign is introduced for the convenience of applying PIRV and LIRV condition indicators. The division of U_{rm} by A_+ in practice presents normalization of U_{rm} by the volume residual insulation polarization value in the moment of the RV measurement beginning. Such normalization allows comparing PIRV for industrial insulators of various geometrical sizes and configurations, for example, for insulating cables of various lengths and cross-sections. Indeed, at any time the $U_r(t)$ curve is determined via two processes in electric insulation: depolarization of volume charge states and conductivity, except one point at the curve – reference point $t_2(0)$ in the time scale (see Fig.2). In point $t_2(0)$ the $U_r(t)$ curve is defined by high conductivity of a metallic conductor (insulation in the $t_1(0) - t_2(0)$ interval shunts with a metallic conductor) and by the depolarization process in insulation.

The division of U_{rm} by S_+ value represents a normalization of U_{rm} by volume charge value, which determines depolarization currents of the short-lived charge states. Such "internal" normalization allows quantitively evaluating the volume insulation conductivity by the LIRV value regardless of its geometrical sizes and configurations.

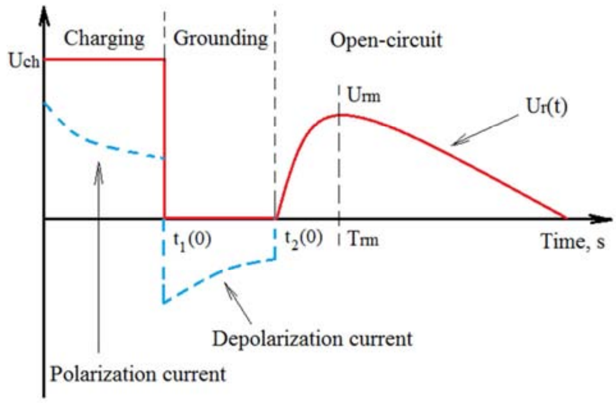


Fig. 2: The process of the recovery voltage curve shaping

As stated above U_{rm}, which means PIRV and LIRV, depends on t_d preliminary charge time. In other words, it's determined by the volume polarization states with relaxations times of about $100 \cdot t_d = 100 \cdot (t_2(0) - t_1(0))$, i.e. in order to estimate changes in the whole spectral distribution of polarization states, one should take measurements at various t_d. The experience already gained by the manufacturers of the CD-31/30 facilities for the RV measuring [2] have shown that the optimum value for the PILC diagnostics is $t_d = 2$ *c*. As a rule, that particular value t_d is set by default in the PILC RV measuring devices.

THE MAIN RESULTS OF THE CABLE CONDITION DIAGNOSTICS

In terms of the works on cable ageing at NPP we've conducted diagnostics of approximately 400 6 kV PILC. The length of the cables mainly makes 50 – 200 m, only some cables were under 2000 m long. Cable lifetime is over 30 years. The main cable routes lay in the premises of the power units outside enclosure vessel (inside enclosure vessel cables of the cross-linked polyethylene are used).

Upon conducting technical diagnosis, as a rule, before the cables are shut down, the heat monitoring of cable routes is carried out, if there's access to them in order to detect "hot points". In order to measure insulation resistivity R_i at 2,5 kV a standard digital megohmmeter is used. For time-space reflectometry of cable lines a "Digiflex COM" reflectometer is used. RV was measured with "AC Tester" device at 2 kV charge voltage, charge time was 30 minutes, preliminary charge time – 2 *s*, RV measuring time – 30 minutes. For the OWTS method implementation the "SPDA 30" facility was used. Additionally for some cables approximate power factor $\tan\delta$ was measured ranging from 0,001 to 1000 Hz using IDA 200 or IDAX 350 facility.

Measurements of $\tan\delta$ were conducted for the assessment of the absolute paper insulation moisture value [6] and for detection of conductivity increase cause: whether it's a consequence of moisturizing or carbonization of paper insulation.

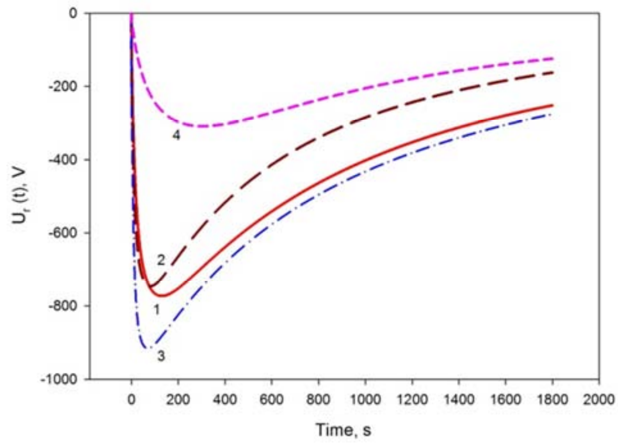
The causes and mechanisms of the PILC ageing have been established. First of all, its shrinkage and ageing of paper insulation at local sections of cable routes due to: 1) heat exchange disruption between a cable and the environment (cable routing in tubes, wall penetration seals, fireproof composition coating); 2) availability of vertical sections of cable routes (areas with depleted oil-rosin saturant are developed). Secondly, this paper insulation moisturizing in sections joining end sleeves (moist ambient air gets “sucked” into insulation due to the pressure difference during electrical unload and core temperature drop).

Cable failures in the premises of NPP units are mainly connected with the impregnated paper insulation shrinkage with consequent paper embrittlement. One can constructively distinguish two different ageing trajectories leading to limit cable states by this mechanism. The first one is when the impregnated paper insulation shrinkage is accompanied by insulation resistivity R_i raise, the limit state comes “unexpectedly”, as a rule, after the occurrence of additional external influencing factors, e.g. temperature raise in a route section or mechanical cable deformation upon carrying maintenance of the nearby equipment. The second one is when the shrinkage is accompanied by the drop of R_i down to the limit value due to paper carbonization influenced by particle charges and the existence of bows of cable routes in insulation shrinkage places, e.g. in the place where a cable “exits” a vertical vault/chute to horizontal level.

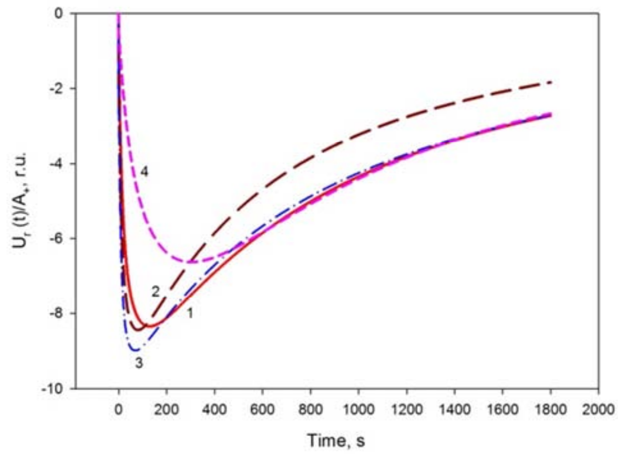
Fig.3 presents typical curves $U_r(t)$ and their derivations deduced by the division of its every value by A_+ value (see Fig.3b) and S_+ value (see Fig.3c) for four representative cables with a different ageing level. The comparison of $U_r(t)$ and $U_r(t)/\mathrm{A}_+$ curve intensities demonstrates what ageing processes prevail in the paper electric insulation, the ageing intensity in numbers should be estimated against the maximum of these curves, i.e. against U_{rm}, PIRV, LIRV parameters (Table 1).

Simultaneously with the U_{rm}, T_{rm}, PIRV and LIRV parameters other technical characteristics were measured (Table 1). It was the insulation resistivity R_i recalculated for a 1 km long cable, polarization index *PI* and absorption factor K_a, and moisture content *W*. The moisture content was deducted by the minimum value, dependence of the approximate power factor $\tan\delta$ on frequency [6]. The presented experimental data (Table 1) is selected by design, since it reflects different typical PILC conditions.

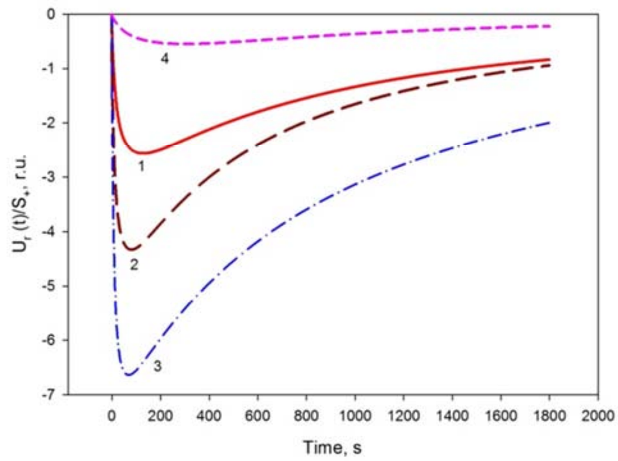
Cable No.1 is of the best technical condition after a 30-year service. It has insignificant insulation moisture, so *W* = 1,2% (for a “dry” cable *W* ≤ 0,5%, for a significantly moist one *W* ≥ 4,0%) and *PI* = 3,5 (for a new cable *PI* ≥ 4,0). Cable No.2 condition is average, moisture content remained practically the same compared to cable No.1, insulation conductivity has increased through paper carbonization in insulation shrinkage places, consequently there’s a R_i and *PI* decrease and LIRV increase. Cable No.3 condition has the limit state evidence due to a deeper shrinkage and paper carbonization rate, the change in R_i, *PI*, LIRV is even more significant, there’s a shift of the RV to the left, despite the fact that cable No.3 is longer that cable No.2. Cable No.4 is in limit condition though R_i is big.



a)



b)



c)

Fig. 3: The recovery voltage curves (*a*) for representative cables and their derivations after normalization to A_+ value (b) and S_+ value (c)

Cable ref. No.	Cable make	Cable length, m	T_{rm}, s	U_{rm}, V	PIRV, r.u.	LIRV, r.u.	R_i, MOhm for 1 km	*PI*	K_a	Moisture content *W*, %
1	TSAABln 3×150	121	129,0	773,0	8,4	2,6	369	3,5	2,7	1,2
2	TSAABln 3×150	85	80,5	746,3	8,4	4,3	297	2,8	2,7	1,3
3	TSAABln 3×150	177	69,5	915,7	9,0	6,6	205	2,5	2,8	1,3
4	SHV-3×240	127	281,0	389,0	7,0	0,7	1560	2,2	2,3	-

It's because of a severe insulation shrinkage, in this case it didn't lead to the volume insulation conductivity increase due to lack of bows and deformation of cable covering on routes, i.e. there are no insulation conductivity through channels, which could be connected with paper carbonization. The polarization properties for this cable are practically lost, there are low PIRV, LIRV and *PI* values; due to lack of saturation between paper insulation layers the volume charge occurring upon charge voltage supply is insufficient for generation of big response in the form of RV, and the curve $U_r(t)$ itself herewith is shifted to the right consequent to the short-lived polarization states (Fig.3).

The gained experience in the complex PILC diagnostics under 6 – 10 kV voltage gave us the basis for determining the condition criteria of these cables according to the PIRV and LIRV values (Table 2).

Cable condition/ Insulation ageing rate	*PIRV* parameter, r.u.	*LIRV* parameter, r.u.
Limit/ Limit rate of insulation shrinkage	*PIRV* ≤ 6,6 and *LIRV* < 0,7	
Operable degraded/ High rate of insulation shrinkage	7,6 > *PIRV* > 6,6 and 0,7 ≤ *LIRV* < 0,9	
Operable with significant deviations/ Average rate of insulation shrinkage	8,7 ≥ *PIRV* ≥ 7,6 and 0,9 ≤ *LIRV* ≤ 1,5	
Normal/ None	*PIRV* > 8,7 and 1,5 < *LIRV* ≤ 2,0	
Operable with insignificant deviations/ Low	8,7≥*PIRV* ≥8,0	2,0< *LIRV* ≤ 3,0
Operable with significant deviations/ Average	8,0>*PIRV* ≥ 7,6	3,0< *LIRV* ≤ 4,5
Operable degraded/ High	7,6>*PIRV* ≥ 6,6	4,5< *LIRV* ≤ 6,5
Limit/ Limit	*PIRV* < 6,6	*LIRV* > 6,5

The RV method by nature is highly sensitive towards registering both developing defects and defects, which are indicative of the cable limit state. RV is a response to the depolarization processes of the dielectric volume defect charge state. However, these states themselves not always can contribute to the conductivity steady leakage current; it especially manifests itself in the multilayer insulation materials. Nonetheless, for the aged 6 – 10 kV PILC there's a good correlation between PIRV, LIRV and R_i (Figure 4).

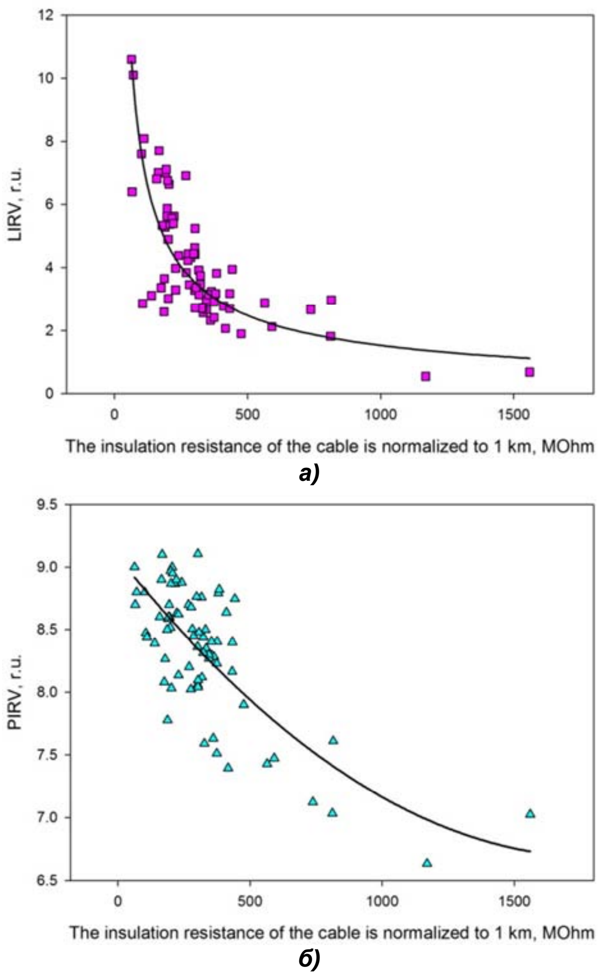


Fig.4: Correlation dependence between insulation resistivity and diagnostics parameters PIRV (a) and LIRV (b)

When defining the cable condition estimating criteria by the PIRV and LIRV parameters cables with different insulation moisture level were selected specifically [5].

In order to deduct PIRV and LIRV parameters it would be enough to carry one RV measurement out, which decreases the time of the PILC technical diagnosis, since custom paper insulation moisture estimating methods are based on the RV measurement with two charge voltages [2-3].

RV measurement allows estimating cable condition as a whole. In order to locate such defects in cable routes as insulation shrinkage the OWTS method was used (Figure 5). Usually such defects are developed in vertical cable routes, in local places with the heat exchange mismatch between cables and the environment. Figure 5 shows a typical example of the paper insulation shrinkage: PD are registered in section 55 – 70 m, in this section the PILC shrinkage is connected with iron conduit cable routing and its fire-proof sealing, cable output out of the conduit in this point is registered on a time-space reflectogram.

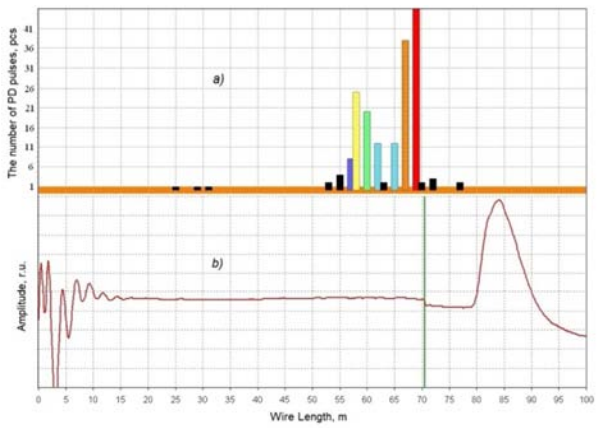


Fig.5: DP distribution along the representative cable (a) length and its time-space reflectometry (b)

The OWTS method has its limits. First of all, it doesn't register defects, which the PD development is impossible in, e.g. in places of moist insulation. Secondly, quantitative assessment of the PILC shrinkage at the basis may give erroneous results, since due to paper carbonization the conductivity increases, which leads to "PD suppression". The last is confirmed by the experimental data gained upon diagnosing 24 power supply cables of electric pumps. All these cables are in service for over 30 years has similar harnessing, including sections of vertical harnessing going into horizontal sections. For cables on the "vertical section – horizontal section" crossover the most of PD pulses are being established. For these cables a trend is observed: as the paper insulation conductivity increases by the LIRV parameter, the number of PD pulses decreases in defect sections registered with the OWTS method (Figure 6).

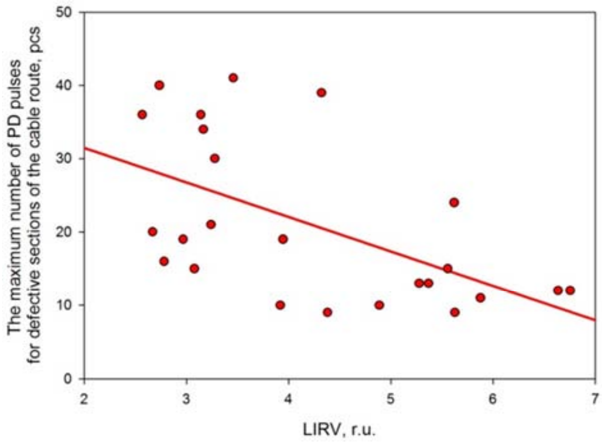


Fig.6: The maximum number of PD pulses in defect cable sections with a different degree of volume conductivity of the insulation

CONCLUSION

The PIRV and LIRV recovery voltage parameters are determined to control the 6 kV PILC condition. Their application will allow controlling the electric insulation ageing against both the change in volume charge state and the change in conductivity. The developed criteria for the classification of the technical condition of these cables based on the parameters PIRV and LIRV.

The PIRV and LIRV application will significantly advance the reliability and efficiency of the electric insulation condition diagnostics. It is achieved through:

1. The possibility of a simultaneous control over two relatively independent insulation ageing processes – the change in volume charge state and conductivity.
2. The physically substantiated experimental data interpretation.
3. The state diagnostics carrying based on the results of only one measurement. For the PILC such an approach reduces cable testing time by two times compared to the customary technique.
4. The possibility to control electric insulation throughout the ageing trajectory from the initial state to the limit state due to the PIRV and LIRV high sensitivity towards volume defects.
5. The potential possibility of using the RV method on the PIRV and LIRV basis for various industrial dielectrics.

REFERENCES

[1] A.P. Tyutnev, R.Sh. Ikhsanov, A.I. Kononenko, and colleagues, 2006, "Physics and Mathematical Model of the Recovery Voltage Phenomenon and the Perspectives of Its Application for Forecasting Polymer Technical Condition", High-Molecular Compounds, A Series, vol. 48, N 11, 2007-2014.

[2] D. Kamenka, M. Beigert, 2002, "Diagnosis at Oil-paper insulation with the method of the Return Voltage Measurement", 17th International Cable Symposium, Zlatibor Yugoslavia, vol.1, 1 – 14.

[3] R. Patsch, D.Kamenka, J.Menzel, 2009, "Return voltage measurements Diagnostic interpretations based on the dielectric time constants", Materials

Science-Poland, Vol. 27, No. 4/2, 1158-1170.

[4] A.I. Kononenko, A.V. Khokhryakov, R.V. Slabous, D.A. Ratnikov, 2012, “The New Recovery Voltage Showings for the Electric Insulation Control”, Electro, N 5, 47-52.

[5] A.I. Kononenko, A.M. Chlenov, A.G. Tsikanin, 2011, "Nondestructive control of condition and prediction of cable life time at nuclear power plants", 19th International Conference on Nuclear Engineering. ICONE19, Chiba, Japan, ICONE19-43243.

[6] R. Neimanis, T.K. Saha, R. Eriksson, 2000, «Determination of Moisture Content in Mass Impregnated Cable Insulation Using Low Frequency Dielectric Spectroscopy», IEEE Power Engineering Society Summer Meeting, Seattle, USA, July 16-20, 463-468.