Impact of Distributed Generation on the Thermal Ageing of Low Voltage Distribution Cables

Gergely Márk Csányi(✉), Zoltán Ádám Tamus, and Árpád Varga

Department of Electric Power Engineering, Budapest University of Technology and Economics, Egry József Str. 18, Budapest 1111, Hungary
{csanyi.gergely,tamus.adam}@vet.bme.hu, varpi950128@gmail.com

Abstract. The low voltage (LV) distribution cable networks were installed some decades ago but the new paradigm in electric power engineering generates new requirements from these old assets. The distributed generation, storage and new appliances can cause high variation of load and reverse power flow, nevertheless the LV cable grid was not designed to these new stresses. The aggregate load and generation can surpass the rated capacity of the cable lines causing short term temperature increasing. This temperature stress can decrease the expected lifetime of the cable lines. In this study the short term thermal overload of LV distribution cables was investigated. The experiments were executed on PVC insulated LV cable samples and electrical and mechanical properties of the cable jacket were investigated. The effect of these short-term overloads on the expected lifetime of cables is introduced and non-destructive measurement for tracking the effect of the short term thermal overloads on the cable is suggested.

Keywords: Distributed generation · Low voltage cables · Distribution network · Cable ageing · PVC cable · EVR · Extended voltage response method · Smart

1 Introduction

Low voltage underground cables play an important role in electricity distribution all across Europe and are valuable assets. Hence, preventing outages, assessing the cables' condition and optimizing replacement strategies are usually the main goals of an electricity provider [1]. Low voltage distribution cables were installed some decades ago, however due to the new paradigm in electric power engineering they have to withstand new stresses. The increasing number of novel appliances connected to the grid (e.g. renewable energy sources, electric vehicles, heat pumps etc.) can easily lead the load to surpass the cable's maximum capacity increasing its temperature [2]. Higher temperature has harmful effects on cable insulation's expected lifetime. However, overloads can be often remain undetected without blowing the fuses that are responsible for the protection of the given cable section while they have a certain thermal effect on the cable, reducing its lifetime. This kind of overload is more likely to happen in the near future due to the aggregated loads generated by the new appliances. In this study the short term thermal overload of LV distribution cables was investigated. The experiments were

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executed on new, PVC insulated LV cable samples and short intensive thermal stresses due to the overloads were simulated by laboratory ageing tests. Electrical (tan δ, voltage responses) and mechanical (Shore D hardness) properties of the cable jacket were measured after the ageing cycles and changing of these parameters was evaluated.

2 Relationship to Smart Systems

As a result of the new paradigm in electric power engineering, low voltage (LV) distribution cables will more often operate in the near future under harmful conditions. The distributed generation, energy storage systems and new appliances can cause high variation of load and reverse power flow, in extreme cases, mostly the photovoltaic systems on hot summer days can cause overloads on low voltage distribution cable lines. These overloads appear when the temperature of the soil is also elevated therefore it can increase the temperature of the core insulation and the jacket over the maximum operation temperature. The increasing temperature decreases the LV distribution cables' expected lifetime. Nevertheless, the LV cable grid was not designed to these new stresses. However, rebuilding the LV cable network would be very expensive therefore the protection of LV assets offers a better solution. Hence, the attention increases on examining how these stresses may affect the LV cables' insulation and how smart solutions can prolong their expected lifetime [2–6]. By means of smart measurements the temperature of the cable sections could be estimated and therefore a more efficient replacement strategy could be developed helping the operators. In order to reach this goal it is essential to examine how LV cable insulations react to the thermal effect of short term overloads.

3 Experimental

3.1 Samples and Thermal Ageing

The samples were prepared from NYCWY 0.6/1 kV 4 × 10/10 mm^2 low voltage cables. The construction of the cable can be seen in Fig. 1. The cable builds up from a PVC jacket (5), wire and tape screens made of copper (4), filling material between (3) the grounding screen and the PVC core insulations (2) and four copper conductors (1).

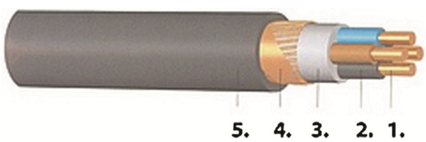

Fig. 1. The construction of the cable

Each cable sample was half-meter long and the wire and tape screens of the cables were connected to all of the core conductors providing an inner electrode while an outer electrode was created by wrapping an aluminum foil around each cable jacket.

To simulate the thermal effects of short time overloading periods the samples were subjected to accelerated thermal ageing. From the cable specimens two groups were created and were aged for 11 h at 125 °C and 140 °C, respectively.

After that a 4-hour-long ageing were carried out at the same temperatures. All in all, the mechanical and electrical properties were measured after 11 and 15 h of thermal ageing. The correlations between the applied and equivalent ageing durations were calculated by means of Arrhenius equation; the activation energy used for the calculation was 80 kJ/mol [7]. Results can be seen in Table 1.

Table 1. Equivalent ageing duration at different temperatures [hour]

80 kJ/mol	11 h @ 125 °C	15 h @ 125 °C	11 h @ 140 °C	15 h @ 140 °C
80 °C	239	326	575	784
100 °C	56	76	133	182

3.2 Measurement

Both mechanical and electrical properties were measured during the investigation. The mechanical parameters were measured by Shore D hardness tester and the dielectric properties were measured by tan δ measurement and Extended Voltage Response (EVR) measurement [8]. The hardness was measured 11 times on each specimen's cable jacket's uncovered part. The measurements can be used only for comparison purposes since the thickness of the jacket is only 2 mm however, the standards (ASTM etc.) require at least 4 mm thickness of the material. The tan δ values were measured 14 times in the 20 Hz…500 kHz range at 5 V. The test equipment was a Wayne-Kerr 6430a impedance analyzer. The EVR method measures the initial slopes of the decay (S_d) and return (S_r) voltages. The decay voltage can be measured after the relatively long duration (100…1000 s) charging period of the insulation. The return voltage can be measured on the charged insulation after a few seconds of short circuiting [9]. By changing the shorting times different time constant polarizations can be investigated. During the EVR measurement the inner electrode (inner cores and wire and tape screens) was connected to 1000 V while the outer (aluminum foil) was grounded. The charging time was set to 4000 s the charging voltage to 1000 V DC and return voltages were measured after 20 different discharging times in the 1…2000 s range. During the investigation the specimens were measured at 23.2 ± 0.5 °C. Proper connections were examined before each electric measurement.

4 Results

Shore D hardness measurement, that is used for characterizing polymers, gives a dimensionless value between 0 (soft) and 100 (hard). The Shore D measurement results in Table 2 show that hardness of the jacket is increasing by the thermal ageing and the degradation at 140 °C is more intensive than at 125 °C.

Table 2. The results of the Shore D hardness measurement of the jacket

Ageing:	New	11 h @ 125 °C	15 h @ 125 °C	11 h @ 140 °C	15 h @ 140 °C
Average	36.95	39.12	40.04	43.46	45.67
Deviation	1.49	1.68	1.57	1.69	1.65

The dielectric parameters were measured by means of Extended Voltage Response method. This measurement provides information about the changing of the conduction by the value of slope of decay voltage (S_d) [10, 11]. The results can be seen in Table 3. As the data of Table 3 suggest the specific conductivity of the jacket material is decreasing by ageing. This suggests the decreasing of the plasticizer content of the jacket.

Table 3. The slopes of decay voltages (S_d) measured on the jacket [V/s]

Ageing:	New	11 h @ 125 °C	15 h @ 125 °C	11 h @ 140 °C	15 h @ 140 °C
Average	76.16	84.42	37.98	50.45	15.60
Deviation	9.14	4.47	9.17	5.55	0.48

The slopes of return voltages as the function of shorting times are in Fig. 2.

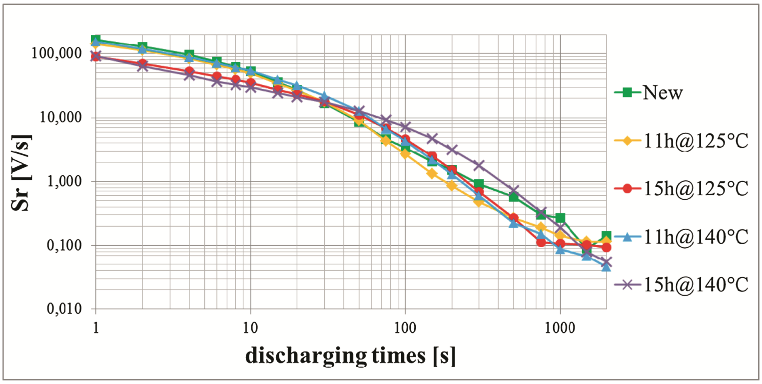

Fig. 2. The slopes of the return voltages (S_r) as the function of shorting times

The result shows that each curve has a certain cut-off point that shifts to the right by ageing. The order from smaller time constants to the faster: New, 11 h @ 125 °C, 11 h @ 140 °C, 15 h @ 125 °C, 15 h @ 140 °C. This also suggests the reduction of the plasticizer content of the jacket.

The tan δ as the function of the frequency can be seen in Fig. 3. The curve of 'New' cable suggests that the peak of the tan δ is over 500 kHz. By ageing, the peaks shift to the lower frequency range. This also suggests the changing of the material structure of the jacket.

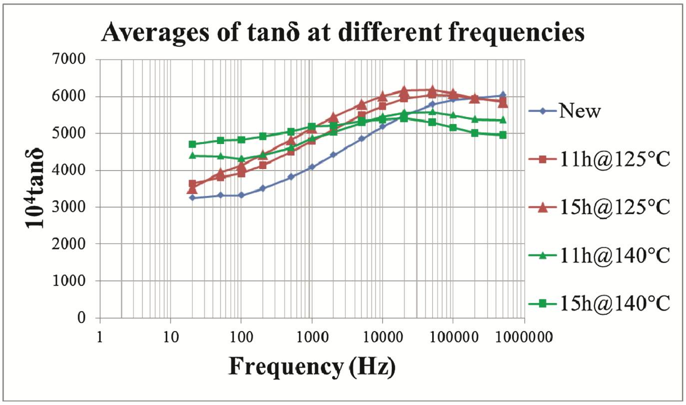

Fig. 3. Tan δ as the function of frequency

5 Discussion of the Results

Previous studies have shown that conductivity and the slow polarization processes above 1 s time constant are strongly influenced by the plasticizer content of the PVC [12]. The slow polarization processes are related to conduction processes e.g. space charge polarization [13]. The thermal degradation of PVC increases [14], however the loss of plasticizer content reduces the conductivity that is directly proportional to the initial steepness of decay voltage (S_d). The slope of return voltage after short (1…3 s) shorting times is directly proportional to the polarization conductivity of slow polarization processes [10].

All of the measurements indicate that the short term but relatively high temperature ageing cycles initiate deterioration processes in the material structure of the jacket.

The shifting of the cut-off point to longer shorting times (Fig. 2) suggests that the most intensive polarization processes become slower. In order to prove this assumption, using an iteration algorithm, the polarization spectra have been calculated from the results of the EVR measurements [8, 9]. Figure 4 shows the calculated spectra.

The result shows that in case of new cables the peak of the most intensive polarization process can be found at 12.6 s. By ageing, the peaks shift towards the higher time constants. The highest time constant peak can be observed at 79.4 s on the samples that were exposed to most intensive ageing (15 h @ 140 °C). Moreover, the shifting of the peaks in the polarization spectrum follows the same order as the changing of the cut-off points in Fig. 2.

The relation between the hardness and the slope of decay voltage is plotted in Fig. 5a. The result shows lower slope of decay voltage (conductivity) correspond to increased

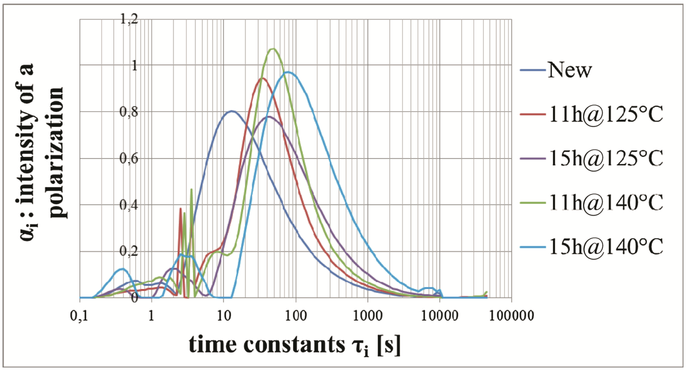

Fig. 4. The calculated polarization spectra

hardness values the only exception is the 11 h @ 125 °C where the slope of decay voltage increased while the hardness also increased. However, the values of different ageing temperatures cannot be fitted to one curve. Similar result can be observed if the slopes of return voltages after 1 s shorting time are plotted as a function of hardness (Fig. 5b).

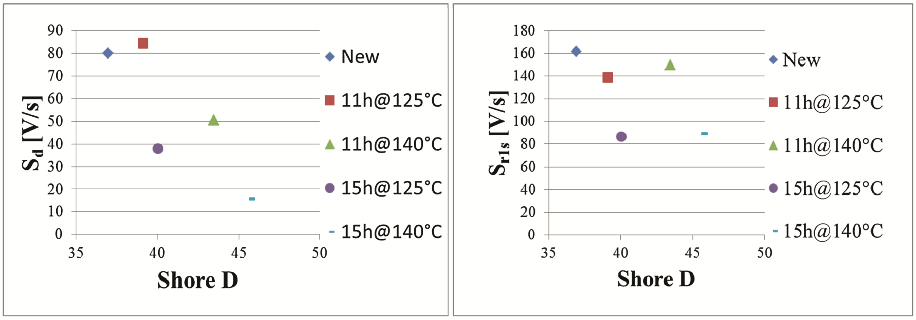

Fig. 5. Slope of decay voltage (S_d) versus Shore D hardness (a,) Slope of return voltage after 1 s shorting time (Sr1) versus Shore D hardness (b,)

The general trend of measuring lower slope of decay voltages by increasing degree of thermal ageing indicates that the dominant process is not the dehydrochlorination but the loss of plasticizer from the PVC. In case of the 11 h @ 125 °C result probably another, faster chemical process (e.g. decomposition of compound) has an effect on the conductivity and later the effect of plasticizer loss becomes dominant, however proving this assumption needs further investigation.

Summing up the results of the study, it can be stated that after the ageing the jacket was not in seriously degraded condition, nevertheless both the mechanical and electrical tests prove the evaporation of plasticizer from the jacket. Moreover, the correlation between the mechanical and dielectric measurements proposes the application of non-destructive dielectric measurements for testing both mechanical and electrical condition of the cable jacket. This would be really useful in practice since the cables are laid under the ground therefore determining the mechanical condition is practically impossible, however by means of EVR method both mechanical and electrical degradations could be investigated.

Although the results are promising, to determine a threshold value for increased probability of failure more investigation is required involving the bending test which is generally accepted in nuclear power plant cable testing [15].

6 Conclusions

The distributed generation in extreme cases, mostly the photovoltaic systems on hot summer days can cause overloads on low voltage distribution cable lines. These overloads appear when the temperature of the soil is also elevated therefore it can increase the temperature of the core insulation and the jacket over the maximum operation temperature. These temperature peaks can initiate degradation processes in these polymeric components of the cable. The effect of the short term thermal overloads on the jacket of PVC insulated low voltage cables was investigated on cable samples. The samples were exposed to periodic thermal ageing test consisting of short but high temperature cycles. After the ageing, the mechanical and dielectric properties of the jacket were tested by Shore D hardness and voltage response measurements, respectively. The results show increasing hardness and decreasing conductive properties of the jacket moreover these properties show high correlation. The relation between these properties enables tracking the effect of the short term thermal overloads by non-destructive dielectric measurements. These results suggest the loss of the plasticizer additive from the jacket material deteriorating the mechanical properties of the jacket. In this condition the jacket is harder and ruptures and cracks can easily appear on it. Therefore, it will not be able to protect the inside of the cable from the environmental stresses e.g. water ingression increasing the probability of the cable failures, which increases the operation risk of low voltage distribution network.

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