

# Investigation of Effects of Short-term Thermal Stress on PVC Insulated Low Voltage Distribution Cables

Semih Bal<sup>1</sup>, Zoltán Ádám Tamus<sup>1\*</sup>

<sup>1</sup> Department of Electric Power Engineering, Faculty of Electrical Engineering and Informatics, Budapest University of Technology and Economics, Egry József Str. 18, H-1111 Budapest, Hungary

\* Corresponding author, e-mail: [tamus.adam@vet.bme.hu](mailto:tamus.adam@vet.bme.hu)

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## Abstract

The main aim of this study is to investigate the ageing process of Low Voltage cables in smart grid. In addition, the behavior of ageing phenomenon has also been investigated. The Low Voltage cable networks were developed decades ago and it is of utmost importance to make comprehensive study over the health of existing Low Voltage cable networks so as to avoid any unprecedented damage. Incessantly increasing energy demand and distributed generation makes it among top priorities to investigate the ageing process of Low Voltage cables.

The effect of thermal stress over dielectrics was investigated as a part of research. To be able to determine these effects the measurements were done on PVC insulated (both cores and jacket) cable by measuring  $\tan\delta$  (dissipation factor), capacitance, return voltage of cable and hardness of insulations. In order to determine thermal effects on dielectric, the measurements were done in different ageing temperature ranges i.e. at 110 °C, 125 °C and 140 °C.

The results of this study support the expectations. The mechanical and the electrical parameters of cable insulation are affected by thermal stress. The dissipation factor and the hardness are increased while the decay voltage slope ( $S_v$ ) is decreased by ageing.

## Keywords

$\tan\delta$ , cable ageing, PVC insulated cable, loss factor, EVR, thermal ageing

## 1 Introduction

Cables are one of the main and important assets of power distribution and transmission systems. The distribution cable networks were built several decades ago. Due to increasing number of electric vehicles and renewable based distributed generation systems, the distribution network assets are affected by new stresses such as repetitive pulses generated by power electronics and short term thermal stresses by rapid time variation of load and generation. It means Low Voltage (LV) cables, which are one of the most important assets of distribution network, will operate more destructive conditions in near future [1–4]. All these factors create irreversible changes in the molecule structure of cable insulation due to some stresses. These changes are called the ageing of insulations.

Ageing of insulation decreases the performance of the system and on the other hand increases the failure rate. Replacing whole distribution cable network and redesigning it according to new requirements can be a solution to prevent those failures and outages. However, this

is not a cost effective way [1–5]. That is why the condition monitoring of currently used cables are strategically important in order to assess the reliability of cable network. There are many existing methods which measure mechanical, electrical and chemical parameters of insulations for condition monitoring [6].

In order to examine how the LV cable insulation is affected by short term thermal stress, the mechanical and the electrical parameters of insulation are investigated in the laboratory of Budapest University of Technology and Economics. Previous studies [3–5] have shown that the effects of thermal stress can be monitored by using well-known techniques such as dissipation factor ( $\tan\delta$ ), Extended Voltage Response (EVR) method and Shore D hardness test. The advantage of these techniques to give an opportunity on-site measurement without removing samples from the network. Furthermore, the activation energy of degradation process by fast repetitive thermal stress was calculated by using the Arrhenius equation.

Using the calculated activation energy the equivalent ageing time in service conditions was determined.

## 2 Experiments

During this study NYCWY 0.6/1 kV 4 × 10 mm<sup>2</sup> type 9 cable specimens are prepared and divided into three groups according to ageing temperature (140 °C, 125 °C and 110 °C). Each group contains 3 cable specimens with 50 cm length (Group A, Group B, Group C).

The structure of cable specimens is shown by Fig. 1, where the numbers represent the part of cables. These are:

1. Copper conductors
2. PVC Core Insulations (black, grey, brown, blue)
3. Filling material
4. Grounding tape
5. PVC jacket.

The minimum ageing temperature is chosen based on IEC 60216 according to Fig. 2 [7].

Thermal class of PVC is considered Y according to STN EN 60085 [7]. As it can be seen in Fig. 2, the minimum ageing temperature of PVC can be set to 110 °C. 15 °C difference is set between the ageing temperatures.

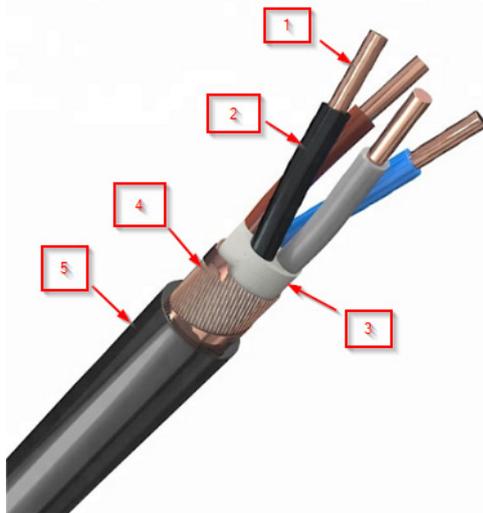


Fig. 1 The structure of cable [3]

Service temperature [°C]	55	75	90	105	120	130	155	180	200	220	250
Thermal class	(55)	(75)	Y	A	E	B	F	H	N	R	(250)
	135	155	170	185	200	210	235	260	280	300	330
	125	145	160	175	190	200	225	250	270	290	320
	115	135	150	165	180	190	215	240	260	280	310
Ageing temperatures [°C]	105	125	140	155	170	180	205	230	250	270	300
	95	115	130	145	160	170	195	220	240	260	290
	85	105	120	135	150	160	185	210	230	250	280
	75	95	110	125	140	150	175	200	220	240	270

Fig. 2 PVC ageing temperature table [7]

The experiments are repeated in 4 ageing cycles. The ageing time was 3 hours in the first 2 cycles after that it is increased to 6 hours in 3<sup>rd</sup> and 4<sup>th</sup> cycles. The electrical properties of core and jacket insulation are investigated by observing the alteration of the dissipation factor and the Extended Voltage Response measurement while the mechanical condition of a jacket is investigated by Shore D hardness test. The room temperature was 23±1 °C during the measurements.

## 3 Measurement methods

### 3.1 The dissipation factor

The dissipation factor is a tangent of angle between capacitive and leakage current if the tested insulation is connected to an AC voltage source. The dissipation factor and capacitance values are measured for each core insulations and PVC jacket, as well in various frequencies (20 Hz.....500 kHz) at 5 V by using Wayne-Kerr Impedance Analyzer. The cable samples are covered by aluminum foil in order to make a conductive surface for measuring jacket. The arrangement of cable sample can be seen in Fig. 3. During the measurement one probe of impedance analyzer is connected to the measured. The other probe is connected to the other three cores which are connected to the grounding screen.

### 3.2 Extended Voltage Response measurement

Since the polarization process (slow polarization process) has a quite important role in ageing studies, previous studies have shown that voltage response method is a useful tool in order to investigate the polarization process of insulations and condition monitoring [5, 8–11].

The voltage response method measures two parameters on charged insulations. These are:

- $S_d$  stands for decay voltage slope.
- $S_r$  stands for return voltage slope.

Based on Professor Endre Nemeth introduction [12], it can be seen that the decay voltage slope is directly proportional to the conductivity of material while the return



Fig. 3 Cable sample

voltage slope is directly proportional to the polarization conductivity. Circuit representation of return voltage measurement can be seen in Fig. 4.

The timing diagram of the Extended Voltage Response measurement can be seen in Fig. 5.

The voltage response method relies on two basic steps. These are charging and shorting of dielectric. These two basic steps are divided into several sections as it can be seen on the timing diagram (Fig. 5). In this study, the cable is charged with 1000 V DC ( $V_{ch}$ ) for 2000 seconds ( $t_{ch}$ ) and total discharging period was 1000 seconds ( $t_{dchn}$ ) which is divided into 20 small timing points ( $n = 20$ ). The decay voltage slope ( $S_d(t_{ch})$ ) was measured just after charging period is over. The return voltage slopes ( $S_r(t_{ch}, t_{dch1}) \dots S_r(t_{ch}, t_{dch20})$ ) were measured after 1 to 1000 seconds of short-circuiting [13] in  $n = 20$  different times in order to investigate slow polarization process, precisely. By adding more discharging time point, the voltage response method can be extended [11]. By doing this different ranges of polarization spectrum can be studied. The previous studies show that Extended Voltage Response measurement is a quite useful tool for condition monitoring of insulations [3–5, 9–11, 13].

### 3.3 Shore D hardness test

As a result of various stresses, the mechanical properties of insulations are changed, as well. The change in mechanical properties of an insulation also indicates the condition of cable. The PVC insulation is very sensitive for high temperature. As a result of ageing, it is observed that the cable loses its softness. Shore D hardness measurement gives

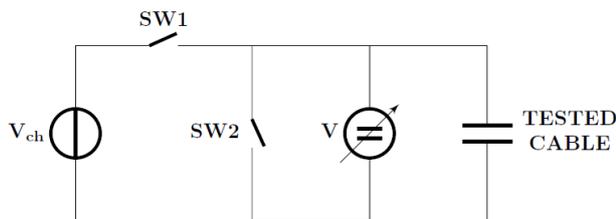


Fig. 4 Circuit representation of return voltage measurement

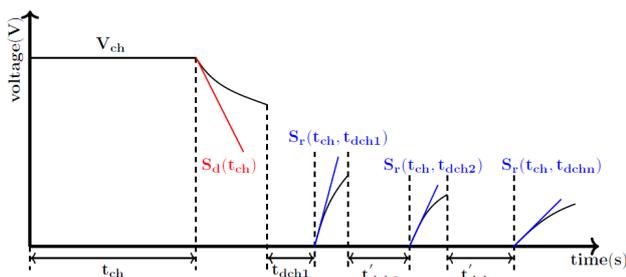


Fig. 5 Timing diagram of voltage response method

a dimensionless result between 0 (soft) and 100 (hard). The measurement is done by taking 10 measurements on each jacket of cable specimens.

## 4 Results

### 4.1 $\tan\delta$ measurement

Fig. 6 and Fig. 7 show the result of loss factor measurement for gray core and jacket at 140 °C. Even though the experiment was performed for three different ageing temperature (110 °C, 125 °C and 140 °C), only the result of cable sample, which was aged with the highest temperature, is shown here.

As a result of 4 cycle measurements, it is observed that the dissipation factor is increased by ageing. It is also observed that the difference between cycles is maximum while the ageing temperature is 140 °C. In addition to this,  $\tan\delta$  values are increased at power frequency level (50 Hz) by ageing in every sample.

The dissipation factor measurement gives the result for the frequency value from 20 Hz up to 500 kHz. Due to the uncertainty of the measurement for the frequencies above 500 Hz, only the results up to 500 Hz are given within Figs. 6 and 7. The trend of  $\tan\delta$  values can be observed clearly up to 500 Hz.

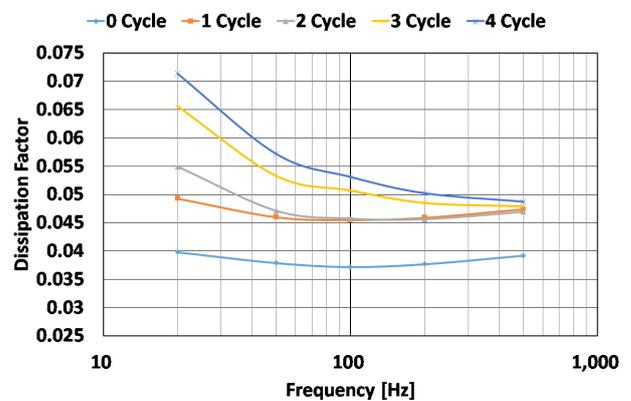


Fig. 6 Loss factor of gray core aging temperature 140 °C

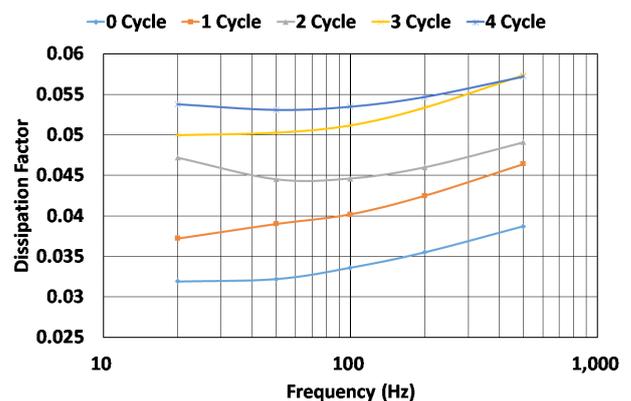
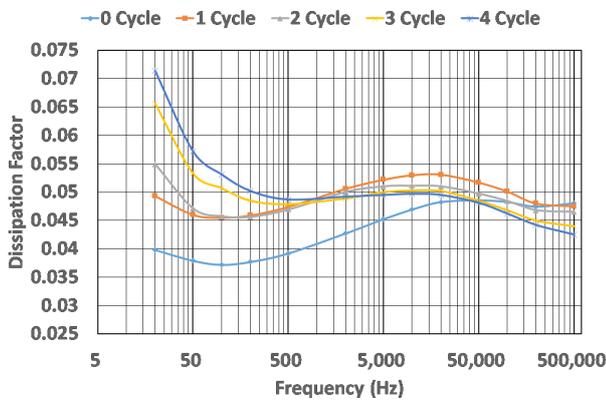


Fig. 7 Loss factor of jacket ageing temperature 140 °C

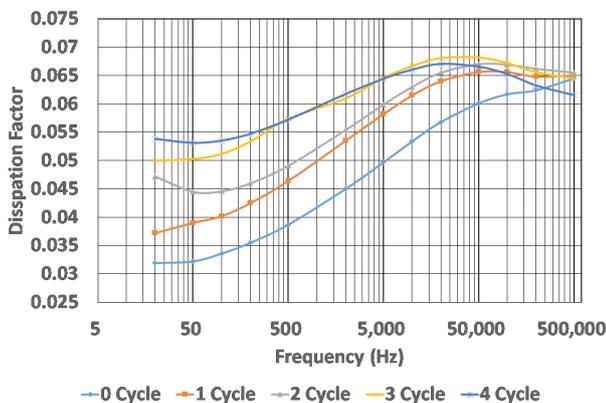
The  $\tan\delta$  values in every cycle have shown first downward trend until 500 Hz then it starts to increase until it reaches its maximum value. It is possible to observe the changings on the peak values during the measurement (Fig. 8). Shifting of the peak frequencies is another result of this measurement. The peak frequencies were shifted to lower frequency level which means space charge (slow) polarization process became more dominant in lower frequency level by the result of ageing. The time constant of polarization process is increased so that the peak frequency is shifted to the lower frequency level by ageing. In order to see the correlation between the peak frequencies and  $\tan\delta$  values, full spectrum of frequencies needs to be checked.

Since the curve becomes flatter especially in peak values with ageing, the weighted (central) frequencies (Hz) are calculated in order to see that how the peak values were shifted. The central frequency ( $f_c$ ) is calculated by using the following Eq. (1) [14]:

$$\log f_c = \frac{\sum_{i=1}^N Df_i \times \log f_i}{\sum_{i=1}^N Df_i} \quad (1)$$



(a)



(b)

Fig. 8 The loss factor of gray core (a) and jacket (b) ageing temperature 140 °C

Table 1 shows the central frequency for the grey core. It can be seen the central frequency is shifted to the lower frequency level by ageing.

### 4.2 Voltage response measurement

The Extended Voltage Response measurement was applied for the only one cable specimen in each group due to the long measurement time. Measurement is repeated for cores and jacket. While measuring the cores; all cores are connected to each other and the voltage probe is connected to them and the ground probe is connected to the grounding screen. For measuring the jacket; the voltage probe is connected to the jacket, which is covered by aluminum foil. Meanwhile, the cores are connected to the grounding screen, which ground probe is connected to. As it is mentioned above, the voltage response measurement gives an opportunity to investigate the polarization process of dielectrics. The studies show that the decay voltage slope is proportional to conductivity. The previous study [8] shows that the evaporation of plasticizer contents decreases the conductivity. The results of this study support the result of the previous study.

Table 2 and Table 3 show how the decay voltage slope is changed by ageing. It can be clearly seen that  $S_d$  values were decreased by ageing. Although the return voltage slope ( $S_r$ ) was investigated carefully, no relation has been found which can be generalized between thermal ageing and the return voltage slope.

### 4.3 Shore D hardness test

The hardness of jacket is measured in order to observe the changing of mechanical properties of insulating material. It is observed that the hardness of the jacket has showed

Table 1 The peak frequencies (Hz)

	140 °C		125 °C		110 °C	
Cycle	Core	Jacket	Core	Jacket	Core	Jacket
0	45888	47000	21838	45700	21789	102040
1	21508	46646	10015	45680	21463	99881
2	9980	46582	9965	45570	21515	46659
3	9979	45424	4057	45109	10009	46266
4	9928	21965	4092	45541	10049	46795

Table 2  $S_d$  values of core

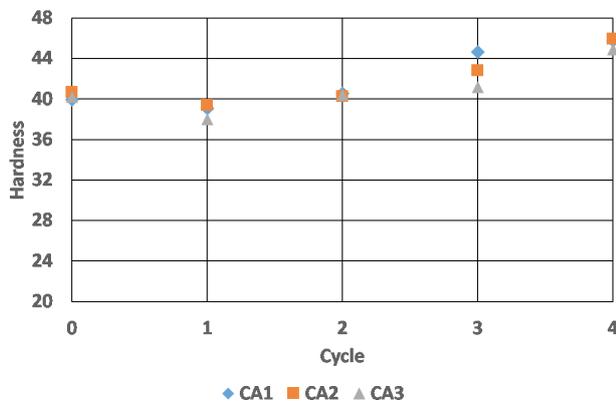
Cycle	$S_d$		
	140 °C	125 °C	110 °C
0	66.957	22.92	26.764
1	74.997	21.008	19.319
2	70.903	14.513	18.059
3	39.98	14.34	13.272
4	29.577	14.06	13.172

**Table 3**  $S_d$  values of jacket

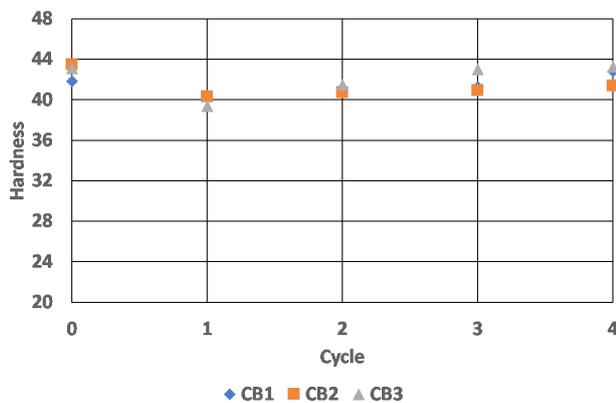
Cycle	$S_d$		
	140 °C	125 °C	110 °C
0	161.86	130.854	144.148
1	150.147	83.733	105.808
2	101.526	71.148	78.424
3	53.589	33.185	55.061
4	27.129	25.6	45.741

upward trend by ageing. The measurement is concluded only for jacket due to thinness (3 mm) of core insulations. The hardness was measured 10 times from the cable jacket. The hardness test is repeated after each cycle and the difference is observed in this study. Previous studies have showed that there is a correlation between the ageing and plasticizer contamination of the material [3, 4, 6, 15]. The result of this study supports the results of previous studies. However, further investigation must be done in order to find the movement of plasticizers.

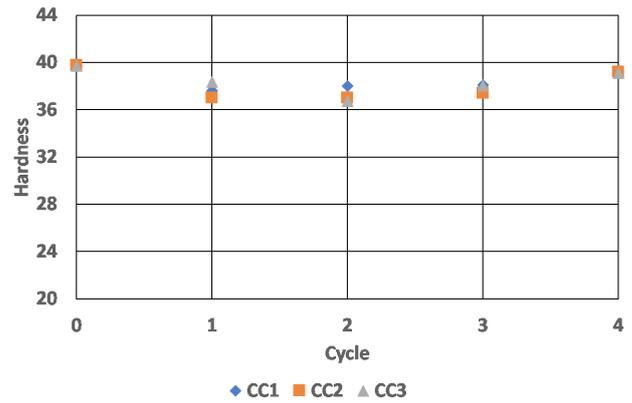
The following figures (Fig. 9, Fig. 10, Fig. 11) show that how the hardness of jacket is changed by ageing in three



**Fig. 9** The hardness of Group A (140 °C)



**Fig. 10** The hardness of Group B (125 °C)



**Fig. 11** The hardness of Group C (110 °C)

group. There is an interesting point in the result. As it can be seen on the figures, the hardness of jacket is decreased after the first cycle. This is the opposite result of our expectations. However, this situation can be explained as following; when the cable is exposed to the thermal stress, the plasticizer molecules evaporate from inner cores and filling material to the cable jacket. So that the hardness of jacket decreased in the first cycle after that it shows an upward trend as it is expected at each temperature level. Also, the steepness is higher in case of 140 °C than 125 °C and 110 °C.

Based on Shore D measurement results, equivalent ageing times are calculated by using the Arrhenius equation. The activation energy of process is also calculated by using the Arrhenius equation (Eq. (2)). The calculated activation energy is 100.171 kJ/mol (~1.0382 eV).

$$\frac{t_s}{t_a} = e^{\frac{E_a}{k} \left( \frac{1}{T_s} - \frac{1}{T_a} \right)} \quad (2)$$

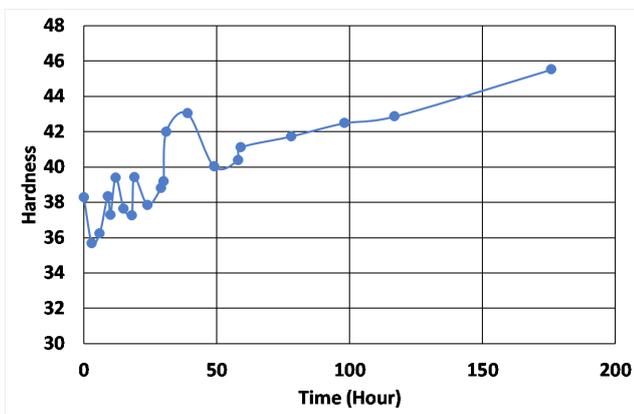
Equation (2) represents Arrhenius equation. Here  $t_s$  represents operating time,  $t_a$  represents equivalent ageing time,  $E_a$  represents activation energy of process,  $k$  represents Boltzmann constant,  $T_s$  represents absolute operating temperature in Kelvin,  $T_a$  represents absolute ageing temperature in Kelvin. Ageing times of Group A and Group B are converted to the equivalent ageing time of Group C by using Eq. (2). Table 4 shows the calculated equivalent ageing times.

80 kJ/mol activation energy is taken from the literature [3, 15]. As it can be seen in Table 4, higher activation energy makes deterioration slower on insulations.

Fig. 12 represents the hardness versus time graph according to calculated ageing times. As it can be seen in Fig. 12, general intention of hardness shows upward trend by ageing as it is expected.

**Table 4** Equivalent ageing times

	110 °C	
	80 kJ/mol	100.171 kJ/mol
3 h-125 °C	8 hours	10 hours
6 h-125 °C	16 hours	19 hours
9 h-125 °C	23 hours	31 hours
12 h-125 °C	31 hours	39 hours
15 h-125 °C	39 hours	49 hours
18 h-125 °C	46 hours	59 hours
24 h-125 °C	61 hours	78 hours
30 h-125 °C	78 hours	98 hours
3 h-140 °C	19 hours	29 hours
6 h-140 °C	38 hours	58 hours
12 h-140 °C	75 hours	117 hours
18 h-140 °C	112 hours	176 hours

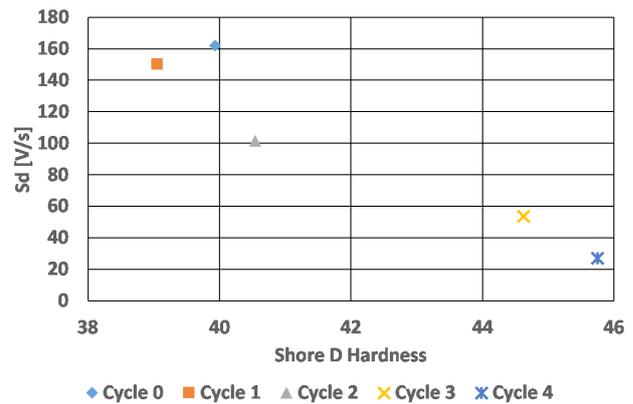


**Fig. 12** The hardness versus time (activation energy 1.0382 eV)

#### 4.4 Comparison of voltage response and hardness measurement

Hardness test measures a mechanical property of the insulation while the voltage response measurement measures an electrical property of the insulation. As it is mentioned in previous sections, hardness of jacket shows upward trend by ageing. On the other hand, the decay voltage slope is decreased by ageing. In the light of these information, mechanical and electrical properties can be compared. Fig. 13 shows the result of comparison for only 140 °C. The other temperatures (125 °C, 110 °C) show similar results.

As it can be seen in Fig. 13, the hardness of cable is increased by ageing while the decay voltage slope is



**Fig. 13**  $S_d$  versus hardness

decreased. Hence the change of mechanical properties can be also investigated by the measurement of slope of decay voltage.

#### 5 Conclusion

The main aim of this study is to investigate the effects of short-term thermal stress on PVC insulated Low Voltage distribution cables. The Low Voltage cables are mainly located underground that is why especially hot summer days the temperature of soil increases. On the other hand, renewable energy production may cause overload on the cable and increase the temperature of cable. Also distributed generation and renewable energy production is getting more common techniques which are connected to the distribution network. Since the cable networks are built some decades ago, the cables may not be strong enough to meet the requirements of new stresses. That is why the ageing studies become quite strategic and important in LV level as well.

The electrical and mechanical parameters of cable insulations were investigated on this study. The dissipation factor and hardness of jacket has increased. On the contrary, the decay voltage slope has decreased as a result of decreasing of conductivity. Comparison of the decay voltage slope and hardness of cable give an opportunity to compare electrical and mechanical properties of the cable. The cables are located underground it is not easy to take them out and measure its properties. It can be seen in this study that the mechanical properties of cable can be predicted by observing of changing of electrical properties of the cable.

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