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EXPERIMENTAL ANALYSIS OF THE EFFECTS OF HARMONICS AND TEMPERATURE ON LIFESPAN OF LOW VOLTAGE CABLES

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ABSTRACT
In this study, the variation of the cable service life of single core and multi-core low voltage cables, with PVC insulated copper conductor, was researched under normal usage conditions and under the effects of harmonic sources by using the experimental analysis data. It is known that temperature of cables is due to losses occurring when current flows through the conductor. How this temperature therefore the losses change according to the current when the cable is used under the normal operating conditions, and according to the current with harmonics when it is used under the effects of harmonic sources, were compared. And the effects on lifespan of the cable were revealed. In this context the effects of harmonic systems on low voltage cables used in all buildings and constructions have been demonstrated and the benefits to be obtained when harmonics are prevented have been revealed.
Keywords: cable life, harmonics, non-linear loads, cable temperature

1. INTRODUCTION
Today, low voltage energy distribution inside the buildings is usually made by using copper cables. Cabling from main energy distribution panel to end point inside the building is done by using electrical conduits or by using cable trunking systems depending on the design of the building. Cable size to be used in the projects is generally determined by the nominal current value calculated according to power factor of the system or of the load and the number of the phases of the system. Conformity analyses of the calculated value are done according to International Electrotechnical Commission (IEC) standards. And nominal current value is calculated by taking into account the environmental temperature, the type of conductor and the installation type of the cables. Variables used in this evaluation are chosen from the tables in IEC 60364-5-52 standard. Additionally a study has been carried out by taking into account the losses and the temperature and it's been revealed that calculating current carrying capacity by using this method is much more accurate. Technology develops rapidly in the century we live. Parallel to developing technology lots of devices which make our life easier is being produced and these devices become indispensable parts of our lives. However it is known that these devices affect our electrical system and this has been the subject to lots of researches. The signal shape of the current they use becomes distorted because the load characteristics of these devices are not linear. This signal is periodic and itand it consist of basic sinusoidal wave and other signals which have different amplitude and frequencies. Different amplitude and frequencies have many harmful effects on the conductor. In addition, it causes an increase in some already problematic situations. For this reason, in addition to the calculation and selection criteria mentioned above, the conductor section selection should be made accordingly by adding the harmonics which are due to various reasons in the system. In this study in order to demonstrate these unwanted situations, temperature variations of single core and multi-core low-voltage cables with PVC insulated copper conductors have been determined by testing them under normal operating conditions and in harmonic conditions. The effect of these temperature variations on lifespan of the cable has been tried to be determined.

2. METHODOLOGY
In this section, basic theoretical knowledge and formulas needed to calculate how the lifespan of the cable is affected by the temperature of the cable due to the harmonic currents that occur due to nonlinear loads in electrical systems are given.
Cables used as main element in low voltage electrical transmission face problems such as variation of frequency, increase in temperature and many kinds of mechanical negative effects due to ambient conditions. The addition of harmonics to these situations, which cause problems even under normal operating conditions, further increases these

problems. Harmonics in the form of multiples of the basic frequency, affect the current and voltage values and shorten the lifetime of the conductor dramatically. Basic cause of shortening the cable lifetime is the chemical effects of these harmful situations. The cable lifetime can be calculated using the Arrhenius Equation. [4]

$$\frac{dp}{dt} = A \times e^{\frac{-Ea}{k\theta}} \qquad (1)$$

The variables and fixed elements in the equation is as follows:
dp/dt = Change in cable life depending on time
A= Frequency Factor (In different sources, it is also defined as the collision frequency of molecules. It provides information on both frequency and direction of collision.)

k= Boltzmann constant ($8,657 \times e^{-5}$ eV/K)

θ= Temperature
Ea=Activation Energy (eV)
If we interpret this equation, it is generally used as;

$$k = A \times e^{\frac{-Ea}{R\theta}} \qquad (2)$$

In this equation;
k: velocity constant
A: frequency factor
R: Gas constant
θ= Temperature

In this equation "$e^{\frac{-Ea}{k\theta}}$"explains the proportion of collisions that have sufficient energy. In equation (1) "k= Boltzmann constant" is used instead of "R: Gas constant". As it is known, "k" is obtained by dividing the gas constant by avogadro constant. By using Boltzman constant more detailed results for smaller physical situations are obtained. The velocity constant is interpreted as dp / dt in order to predict how the cable life will change over time in the event of an increase in temperature. As a result, the equation for the change in cable lifetime depending on the temperature can be written as; [3]

$$p = p_i \times e\left(\frac{-Ea}{k}\right) \times \left(\frac{\Delta\theta}{\theta_i\left(\theta_i + \Delta\theta\right)}\right) \qquad (3)$$

The variables and fixed elements in the equation is as follows:
Δθ: Amount of increase in temperature (K)
θi: Cable operating temperature (K)
Ea: Activation Energy (eV)

k= Boltzmann constant (8,617. e^{-5} eV/K)

p: Δθ lifetime of temperature increase (day)
Pi : Life of θi temperature (day)

2.1 Experimental Study

Experimental observations were made by using 3x2,5 mm² and 3x1,5 mm² 0,3 / 0,5 kV low voltage multi core cables and 1,5 mm² 0,3 / 0,5 kV low voltage single core cables. The 3x2,5 mm² cable used in the experiment is PVC insulated, PVC filled and has 3 2,5 mm² single wire copper conductors and PVC outer sheath. (Figure 1). The outer diameter of the cable (approx.) is 10.2 mm, the current carrying capacity is 30 A, the conductive DC resistance is 7.41 ohm / km and the cable weight is approximately 185 kg / km.

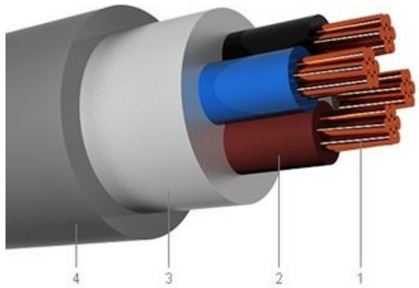

Figure 1 3x2,5 mm² and 3x1,5 mm² 0.3 / 0.5 kV low voltage multi-core cable

1-Single wire copper conductor (multi-wire version available)
2-PVC insulation
3-PVC filler
4-PVC outer sheath

The 3x1,5 mm² cable used in the experiment has three 1.5 mm² single-wire copper conductors, PVC insulated, PVC filler and PVC outer sheath (Figure 1). The outer diameter of the cable (approx.) is 8.9 mm, the current carrying capacity 22 A, the conductor DC resistance 12.1 ohm / km and the cable weight (approx.) 130 kg / km. It looks like Figure 1 in appearance.
Another cable used in the experiment is a PVC insulated 1.5 mm² cable, which has 1.5 mm² single-wire copper conductor.(Figure 2). The outer diameter of the cable is 2.75 mm, the current carrying capacity is 24 A, the conductor DC resistance is 12.1 ohm / km and the cable weight is (approx.) 20 kg / km.

Figure 2 1.5 mm² single core low voltage cable

1-PVC insulation
2-Single core copper conductor

i. **Aplication Stages**

Each cable type used in the experiment was prepared as identical pairs in equal lengths. The cables were connected individually between a power supply and load group to allow current flow at current carrying capacity limits. Cables were firstly connected between the power source and the linear load which would not produce harmonics, the heating of the cable was observed and temperature measurements were made at certain intervals. Then identical of this cable was connected between power source and nonlinear load, power of which was same as linear load. And current drawn was at the same amperage value. Under this situation, temperature measurements were made on the cable at regular intervals and these values were recorded and compared. These operations were applied individually for all cable types described above.
3x2,5 mm² 0,3 / 0,5 kV low voltage multi-core cable was first connected between the source and the linear load to provide a current of 30 A . In this case, the temperature on the cable was measured and the temperature change for a certain period of time is given in the table below.

Table 1: Time-dependent change of temperature of a 3x2.5 mm² 0,3 / 0,5 kV low voltage multi-core cable when a current of 28 A is drawn under a linear load.

Time of Measurement (minute)	Temperaure (°C)
0 (Beginning)	30 °C (Ambient temp.)
3. Minute	41 °C

5. Minute	44 °C
7,5. Minute	49°C
10. Minute	52.2 °C
15. Minute	56,4 °C
17,5. Minute	60 °C
20. Minute	63 °C
25. Minute	65.4 °C
27,5. Minute	66,1 °C
30. Minute	66,2 °C

Recorded values for 30A current carrying 3x2,5 mm² cable are demonstrated above. As you can see, the temperature is increasing gradually and saturating at one point. After this point, the temperature value was remained almost the same, and no increase was observed. Then identical of this cable was connected between power source and nonlinear load. Power of nonlinear load was same as linear load. Providing a current of 30 Amps, temperature changes on the cable were measured and recorded to table below.

Table 2: Time dependent change of temperature of a 3x2.5 mm² 0.3 / 0.5 kV low voltage multi-core cable when 30 A current is drawn under a non-linear load.

Time of Measurement (minute)	**Temperaure (°C)**
0 (Beginning)	30 °C (Ambient temp.)
3. Minute	45 °C
5. Minute	48°C
7,5. Minute	53.4 °C
10. Minute	58 °C
15. Minute	64.5 °C
17,5. Minute	68 °C
20. Minute	70 °C
25. Minute	72.3 °C
27,5. Minute	73 °C
30. Minute	73,1

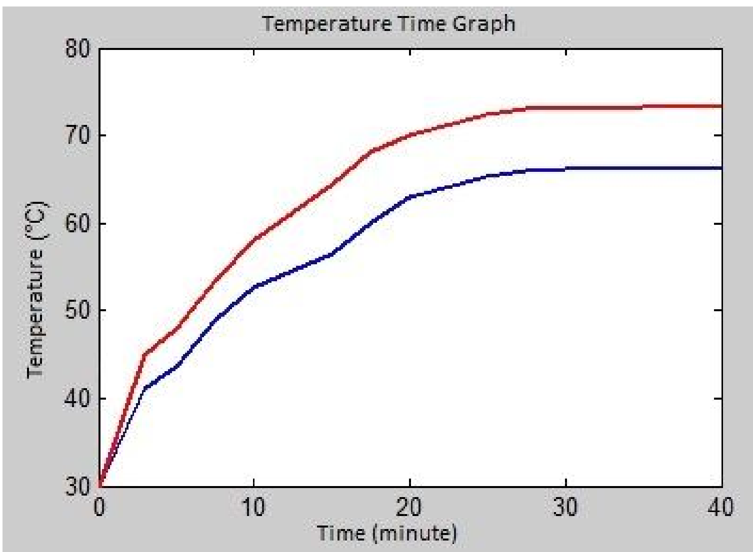

Figure 3 Temperature-time graph of 3x2,5 mm² 0.3 / 0.5 kV low voltage multimode cable for both load cases

As it can be seen in the graph, the temperature on the cable also increased gradually in the measurements made for the second case, and after a while the temperature increase remained almost the same. However, it is evident that the increase in temperature is higher than in the first case.

The same procedure was applied for low voltage cable with 3x1.5 mm² single wire copper conductor. It was connected between linear load and source and non-linear load groups and source, respectively, to provide a current flow of 22 A, and temperature measured at certain intervals were recorded.

Table 3: Time-dependent change of temperature of a 3x1,5 mm² 0,3 / 0,5 kV low voltage multicore cable when a current of 22 A is drawn under a linear load.

Time of Measurement (minute)	Temperature (°C)
0 (Beginning)	30 °C (Ambient Temp.)
3. Minute	42 °C
5. Minute	45 °C
7,5. Minute	48.4 °C
10. Minute	51.2 °C
15. Minute	55.6 °C
17,5. Minute	59 °C
20. Minute	62.6 °C
25. Minute	66 °C
27,5. Minute	68 °C
30. Minute	68 °C

After this process, the variation of the temperature of the cable with a current of 22 A over time under non-linear load of equal length of 3x1.5 mm² cable was observed and measured values were recorded.

Table 4: Time-dependent change in temperature of a 3x1.5 mm² 0.3 / 0.5 kV low voltage multimode cable when a 22 A current is drawn under a non-linear load.

Time of Measurement (minute)	Temperature (°C)
0 (Beginning)	30 °C (Ambient Temp.)
3. Minute	47,6 °C
5. Minute	51.6 °C
7,5. Minute	55 °C
10. Minute	59 °C
15. Minute	64.2 °C
17,5. Minute	67 °C
20. Minute	71.4 °C
25. Minute	75 °C
27,5. Minute	75.1 °C
30. Minute	75.2 °C

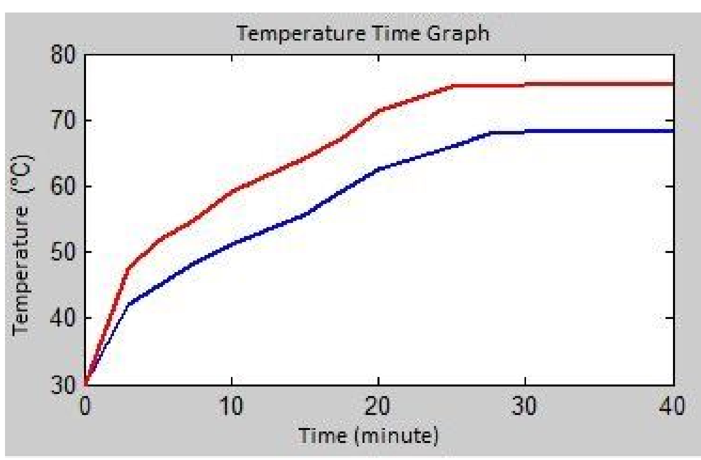

Figure 4 Temperature-time graph of 3x1.5 mm² 0.3 / 0.5 kV low voltage multi-core cable for both load cases

Finally, a 1.5 mm² single-core low-voltage cable was connected between linear load and source and between non-linear load and source, and the cable temperature change was measured and recorded when the current is 22 A.

Table 5: Time-dependent change in temperature of a 1,5 mm² 0,3 / 0,5 kV low voltage single core cable when a 22 A current is drawn under a linear load.

Time of Measurement (minute)	Temperature (°C)
0 (Beginning)	30 °C (Ambient Temp.)
3. Minute	43 °C
5. Minute	46.2 °C
7,5. Minute	49 °C
10. Minute	52.6 °C
15. Minute	57.3 °C
17,5. Minute	61 °C
20. Minute	65 °C
25. Minute	68.6 °C
27,5. Minute	69°C
30. Minute	69.1 °C

Table 6: Time-dependent change in temperature of a 1,5 mm² 0,3 / 0,5 kV low voltage single core cable when a 22 A current is drawn under a nonlinear load.

Time of Measurement (minute)	Temperature (°C)
0 (Beginning)	30 °C (Ambient Temp.)
3. Minute	49 °C
5. Minute	53 °C
7,5. Minute	56.8 °C
10. Minute	61 °C
15. Minute	65,4 °C
17,5. Minute	70 °C
20. Minute	73 °C
25. Minute	75.8 °C
27,5. Minute	76°C
30. Minute	76,1 °C

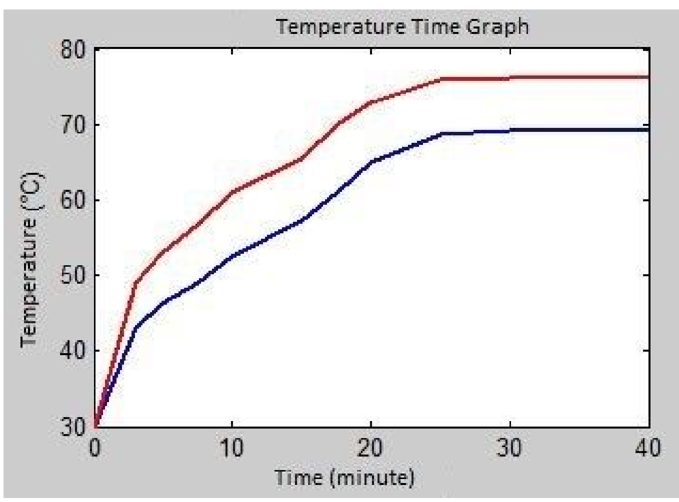

Figure 5 Temperature-time graph of 1.5 mm² 0,3 / 0,5 kV single core low voltage cable for both load cases

In this experiment, the temperature changes of 3 different cables at the same amperage value for a harmonic generating loads and non-harmonic loads, were measured and the recorded values were given in the tables above. Temperature variations under the same conditions for two different load types of each cable were separately graphically interpreted and compared. The reason of using the cables that have same length and same characteristics was to ensure that cables have same resistance and same properties. In this way, it was made possible comparing the two different situations more accurately under the same conditions.

2. NUMERICAL ANALYSIS

Experimental data for three types of cables have been collected and are shown in tables and graphs where the temperature increase under each nonlinear load is significantly greater. At this stage, the effect of this temperature change on the cable service life was calculated using equation (3) and the results are given in Figure 6, Figure 7 and Figure 8.

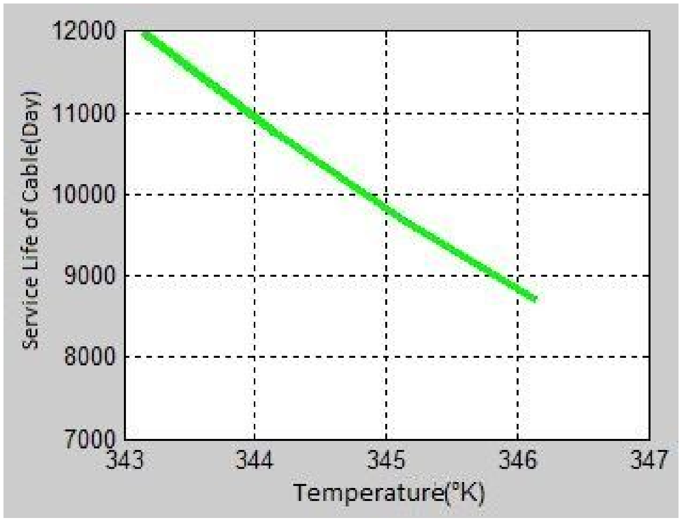

Figure 6 Effect of temperature variation under non-linear load on the life of “3x2.5 mm² 0.3 / 0.5 kV multicore low voltage cable”.

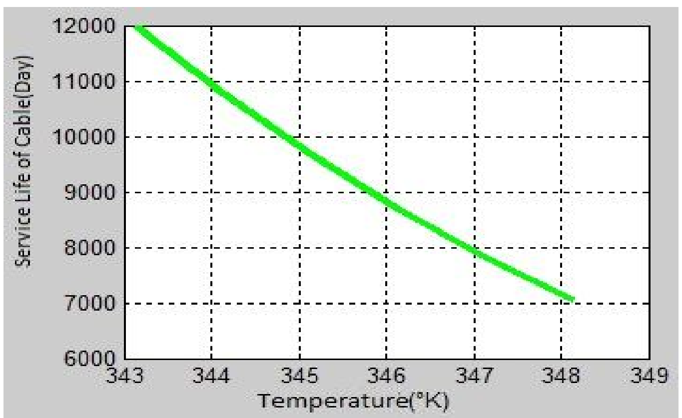

Figure 7 Effect of temperature variation under non-linear load on the life of “3x1.5 mm² 0.3 / 0.5 kV multicore low voltage cable”.

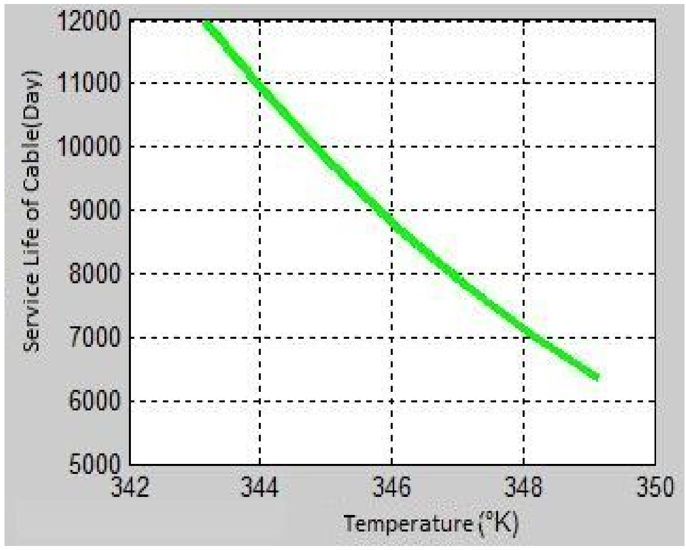

Figure 8 Effect of temperature variation under non-linear load on the life of "3x1.5 mm² 0.3 / 0.5 kV singlecore low voltage cable".

4. RESULTS

In this study, temperature variations of single core and multicore different sizes low voltage cables, when same level of current at the current carrying capacity of the cables, flows under normal conditions and under harmonic generating loads were observed. These temperature changes were compared and finally a calculation was made for the effect of the temperature variation in the harmonic state of the cables used in the experiment on the cable life and the results are given graphically.

As can be seen from the tables and graphs, for each cable type the temperature increase under harmonic currents is higher. Temperatures measured on all cables reach saturation after a certain point. This situation can also be likened to the "terminal velocity" situation. The reason why the temperature reaches saturation is the heat that the cable gives to the environment. After one point, the heat that cable gives becomes almost equal to the heat it receives and the temperature increase stops and the temperature stabilizes.

Conductors have inductive properties. Due to harmonics occurring in the system, frequency also increases. As a result of increase in frequency, the current will flow more than the conductor outer surface, and the increase in skin effect due to the cable harmonics will heat up the cable more. On the other hand when multi-core cables are arranged side by side in electric distribution systems, approach effect is taken into consideration and this is also a factor increasing the cable temperature. Harmonics make enhancing effect on both cases and reduce the cable lifetime. In addition, the 1.5 mm² single-core cable heated to a relatively high temperature, despite it has the same cross-section and length with 3x1.5 mm² cable. In this case, skin effect on single core cables is more effective than that of multi-core cables.

It is known that in systems where single-phase loads are present, 3.harmonics and threefold harmonics are predominant. Since there are single-phase loads in the test system, it is inevitable that the third harmonics dominate. Since there is no phase difference between the third and three-fold harmonics, they strengthen each other rather than damping each other, which in turn reduces the cable life. Furthermore, under the linear load and nonlinear load, the same level of current passed through the cables in the experimental work. These levels were measured by effective value calibrated multimeters. The frequency changes because of the harmonics. For this reason, devices that receive a reference point of zero can not make an accurate measurement. Because there is a difference between the expected zero-point transition in the case of normal network frequency (50 Hz) and the transition in the harmonic state. As it is understood from this, although the current flows at the same level, the harmonics formed in the system constitute a hidden danger. If the system is considered to be much more complex, the effect of the harmonics will extend to different areas. A load group which has a nonlinear load characteristic will draw harmonic current from the system. This harmonic current drawn by nonlinear load, causes harmonic voltage in other parts of the system. Devices with linear load characteristics and the cables connected to them are also affected by this and consequently the lifetime of cables reduces.

The study clearly shows that harmonics occurring in electrical systems significantly affect low-voltage cables, reduce their lifetime, and cause economic problems. In order to reduce and relatively prevent this situation, the devices to be used from the lighting elements to the computers during the project phase for the low voltage systems should be determined and the systems should be designed accordingly. The harmonic effect definitely should be taken into account when choosing the cable sizes as well.

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