

SERGIUSZ BORON

## The effect of duty type on current-carrying capacity of mining power cables

*The methodology for determining intermittent or short-time current-carrying capacity has been described in the article. Results of current rating calculations for a short-time load and the time of cooling to an ambient temperature have been presented.*

Key words: *current-carrying capacity, mining power cables*

### 1. INTRODUCTION

The existing standard [1] for the current-carrying capacity of mining power cables contains principles of selection for continuous and short-circuit loads. The standard concerning motor ratings [2] singles out continuous running as well as other types of duty for electrical motors. The load can be described numerically (load power varies over time in a known manner), graphically, or by choosing one of predefined load types S1 to S10 (actual load should not lead to thermal effects greater than that selected). Duty type S1 corresponds to continuous operation at a constant load; duty type S2 – to short-time duty; S3 through S5 – intermittent periodic duty; and S6 through S10 – continuous operation periodic duty with variable load. Short-time duty can be defined as an operation with a steady load lasting a particular amount of time that is shorter than the time needed to obtain a steady temperature. Subsequently, a standstill time ensues, during which the cable's temperature sufficiently approaches the temperature of the surroundings (Fig. 1).

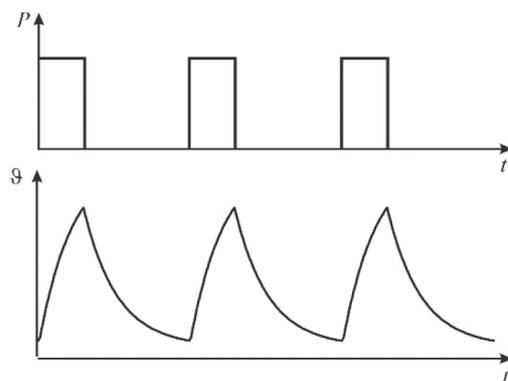


Fig. 1. Temperature run during load-type S2

Intermittent duty is defined as a sequence of identical cycles that may include (depending on the duty type) periods of load, rest, starting, and braking. The motor's manufacturer should specify the rated power for a given type of operation; if the latter is not specified, power refers to load-type S1.

Should extra elements be a part of the machinery, parameters will also apply to these. Power cables are loaded in a manner similar to the supplied machine's motor. If the actual load type is different than S1, failure to take it to account when selecting the nominal cross-sectional area of conductors may lead to:

- unjustified inflation of conductors' cross-sectional area and, as a result, increasing the costs of installation if the actual load induces a temperature rise smaller than continuous operation;
- excessive temperature rise, if the actual load evokes thermal effects greater than continuous operation; this can be a result of frequent and heavy motor starting and electric braking (S4 or S5 duty types).

In practice, especially if longwall machines (such as shearers and chain conveyors) are concerned, the actual load type is similar to intermittent; however, taking into account the random nature of load fluctuations, it proves virtually impossible to attribute one of standardized duty types to such machines. Other machines in turn (such as cyclic operating pumps) are satisfactorily attributable to one of the predefined duty types. This article analyzes the heating and cooling processes for short-time duty operating cables. The same methodology of calculation and analysis can be applied to other load types.

## 2. CALCULATION OF CURRENT-CARRYING CAPACITY

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The values of continuous current-carrying capacity for different groups of mining cables are specified in standard [1]; however, due to the fact that similar cables produced by different manufacturers tend to vary in design, the ratings stated by the producer may deviate from the standard. These differences do not exceed 2–3% and are caused by the varying conductor diameters as well as the thickness of the structural elements. Current-carrying-capacity values can be determined experimentally; however, it is rather impractical and requires long-term measurements that must be performed for each nominal cross-section and every cable type. The oldest and still most-widely-used method of calculating current-carrying capacity is one based on a thermal analogy to Ohm's law; it involves the use of many simplifying assumptions and geometric coefficients determined in an approximate or empirical fashion. In the case of atypical cable structures or an unconventional way of their positioning, this method is prone to giving ambiguous results [3]. When determining the capacity for a duty type other than continuous (such as intermittent and short-time), it is necessary to make further simplifying assumptions; e.g., ones concerning the thermal time constant's stability. Furthermore, the nonlinearity (raised in a number of issues) leads to an insufficient accuracy of the calculations provided by those simplified models.

Heat flow by conduction is described by Fourier's law, according to which heat flux density  $q$  is directly proportional to gradient of the temperature  $\vartheta$ :

$$q = -\lambda \text{grad} \vartheta \quad (1)$$

where  $\lambda$  – thermal conductivity coefficient.

The temperature field inside a cable can be written by means of the Fourier-Kirchhoff equation:

$$\vartheta - \frac{\sigma c}{\lambda} \frac{\partial \vartheta}{\partial t} = -\frac{q_v}{\lambda} \quad (2)$$

where:

- $c$  – specific heat capacity [J/(kg·K)],
- $\sigma$  – body mass density [kg/m<sup>3</sup>],
- $q_v$  – heat source's volumetric rate of heat generation [W/m<sup>3</sup>].

Finding the result for Equation (2) is sufficient for finding the temperature, given that the initial and boundary conditions are specified.

Obtaining an analytical result of differential Equation (2) describing the temperature field is only possible in specific cases regarding simplified regularly-shaped models (such as in uninsulated cables). Insulated power cables are characterized by a complicated geometry with internal heat sources and fluctuating boundary conditions. In cases like these, the problem can be solved solely by numerical calculations [4]. The calculations in this paper have been conducted using the finite element method (FEM).

The essence of FEM is the possibility of approximating every physical quantity (in this case, temperature) by means of a discrete model based on the so-called test function.

The discrete model is created by specifying a finite number of nodes dividing the area in question into a finite number of elements that depict the area's shape as accurately as possible.

The method encompasses calculating the temperature in the nodes, and the temperature inside the element is approximated by a certain polynomial, provided that the polynomials ensure the continuity of temperature on the elements' borders.

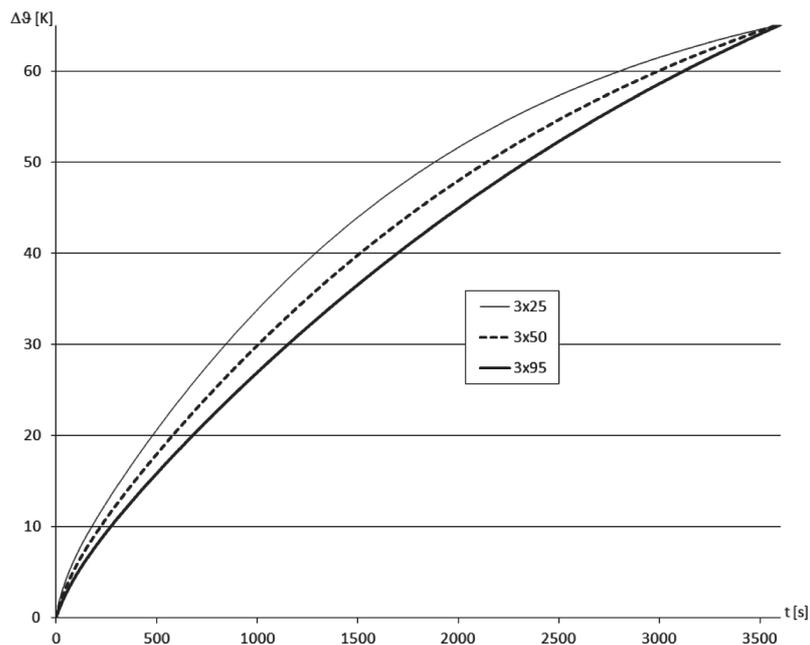
## 3. CALCULATING THE CURRENT-CARRYING CAPACITY FOR SHORT-TIME DUTY

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In order to determine the possibility of increasing the load capacity of cables supplying motors operating on short-time duty, calculations were conducted for the heating and cooling of mining power cables. These calculations were made for OnGcekz-G 0.6/1 kV flexible cables for the nominal cross-sectional area of conductors of 25 mm<sup>2</sup> to 95 mm<sup>2</sup> (the same methodology of calculation may also be used for other types of cables). Table 1 shows the numerical values of short-time duty current capacity for operation S2 60 min, S2 30 min, and S2 15 min (values of continuous current rating are given for comparison). Relative values (in %) in relation to the continuous current rating are also shown.

**Table 1**  
**Calculated values of continuous and short-time current rating for OnGcekz-G type cables**

Nominal cross-sectional area of conductors [mm <sup>2</sup> ]	S1 (continuous load)		S2 60 min		S2 30 min		S2 15 min	
	A	[%]	A	[%]	A	[%]	A	[%]
25	152	100	161	106	183	120	224	147
35	187	100	202	108	236	126	292	156
50	233	100	258	111	306	131	382	164
70	288	100	330	115	398	138	502	174
95	345	100	410	119	502	146	637	185



*Fig. 2. Conductors' temperature rises in time during heating with current equal to capacity for duty-type S2 60 min*

Figure 2 shows the temperature rise over time for cables of conductor diameters of 25 mm<sup>2</sup>, 50 mm<sup>2</sup>, and 95 mm<sup>2</sup>. The depicted values concern the temperature of insulation at its hottest spot; in practice, equal in value to the temperature of the conductors. It was assumed that, in time  $t = 0$ , the cable's temperature was equal to the temperature of the surroundings (25°C).

It should be noted that the course of the temperature during heating slightly diverges from exponential [4] due to the nonlinearity of the problem – the heat transfer coefficient in reality depends on the temperature of the surface that transfers heat to the surroundings. Due to this factor, we cannot speak of a thermal time constant value; nevertheless, a slower increase of temperature is observed for cables with a greater conductor diameter.

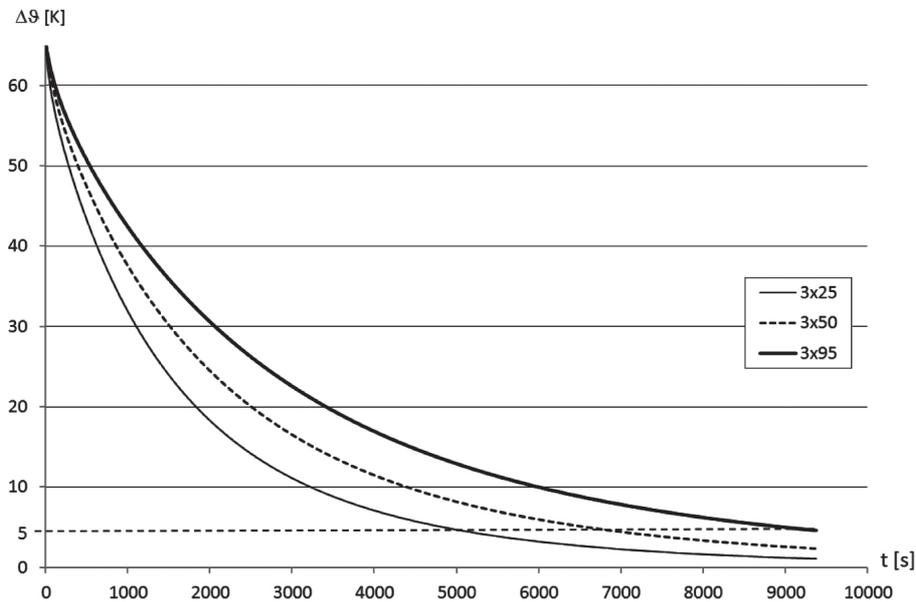
Should duty be maintained for a period of time that is longer than established, will the permissible

temperature be exceeded? The small and short exceedance of the permissible temperature do not have long-term effects, but greater and long-lasting ones can negatively influence a cable's lifetime. Table 2 depicts the time after which the permissible increase of temperature exceeds 10 K, 20 K, and 30 K, respectively.

In standard [2] regarding rotating electrical machines, the minimal rest (standstill) time for short-time duty is defined as the time needed to cool the machine so that the difference between its temperature and the temperature of the coolant does not exceed 2 K. Due to the fact that the cables are air-cooled, this paper assumes that the rest time is long enough for the cable to cool down to a temperature of a maximum of 5 K greater than that of the surroundings. Figure 3 shows the temperature rise during the cooling of cables with the different conductors' cross-sectional areas.

**Table 2**  
**Time (in seconds) after which permissible temperature of insulation (90°C)**  
**will be exceeded by 10 K, 20 K, or 30 K when load of cable lasts longer**  
**than specified by duty type**

Nominal cross-sectional area of conductors [mm <sup>2</sup> ]	S2 60 min			S2 30 min			S2 15 min		
	10 K	20 K	30 K	10 K	20 K	30 K	10 K	20 K	30 K
25	–	–	–	610	1570	–	220	430	680
35	4160	–	–	520	1210	2280	200	400	630
50	2050	–	–	460	1020	1770	190	380	590
70	1550	5920	–	430	930	1520	180	370	560
95	1230	3300	–	390	790	1340	180	360	540



*Fig. 3. Insulation temperature rise during cooling of cables with different conductors' cross-sectional areas after being heated by load current for S2 60 min duty-type*

Table 3 depicts the cooling time for cables heated with permissible load resulting from the type of operation (current specified in Tab. 1). The results of these calculations are to be treated indicatively, as in reality, the cooling conditions may differ from those assumed. Some factors that may influence the cooling process are the temperature of the surroundings, air movement, proximity of other cables, routing of the cables, etc. The values of time shown in the table correspond to the temperature of the conductors; the variability of temperature for other elements is different due to the inertia of the heat-conduction processes.

**Table 3**  
**Cooling duration (down to 30°C) after cable has been heated by current for different duty-types**

Nominal cross-sectional area of conductors [mm <sup>2</sup> ]	Cooling time (in seconds) to 30°C for cables heated by current for duty-type:	
	S2 60 min	S2 15 min
25	4870	2030
35	5720	2840
50	6610	3660
70	7710	4690
95	8970	5860

It follows from the calculations that the cooling time of a cable depends on the heat-inducing duty type. The cooling time for duty S2 15 min is considerably shorter than for duty S2 60 min; this can be explained by the fact that, for a greater but shorter-lasting duty (S2 15 min), the amount of heat accumulated in the cable is less than for smaller but longer-lasting duty (S2 60 min). This in turn stems from the fact that, as the duty terminates, the temperature of the cable's outer layers is heavily dependent on the duty-type. For instance, if a cable with a conductor area of 95 mm<sup>2</sup> is considered, the temperature of the coolest point of the outer sheath after completing operation cycle S2 15 min is equal to 36°C, whereas for cycle S2 60 min, it amounts to 53°C.

#### 4. CONCLUSIONS

On the basis of the analyses and calculations conducted in this paper, the following conclusions may be drawn:

- 1) A cable's current-carrying capacity depends on the duty type of the supplied machine, and this capacity may vary in value from a few to up to several dozen percentage points greater in the case of short-term duty than with continuous load. These values depend on the period of duty as well as the nominal cross-section of the cable's conductor.
- 2) Long-lasting duty of increased current results in the insulation's long-term exceedance of permissible temperatures. These consequences can be especially damaging for cables with a smaller cross-section of conductors.
- 3) The time needed for a cable to cool down to a temperature similar to that of the surroundings is linked to the cross-section of the cable's conductors and type of operation. This value of time ranges from approx. 2.5 h (for cables with greater cross-section conductors heated with duty S2 60 min) to slightly above 30 min (for cables with smaller cross-sections for duty S2 15 min).

The methodology presented in this article can be used for calculating the current-carrying capacity of cables of any construction and any type of duty.

#### References

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*SERGIUSZ BORON, Ph.D., Eng.  
Department of Electrical Engineering  
and Automation in Industry  
Faculty of Mining and Geology  
Silesian University of Technology  
ul. Akademicka 2A, 44-100 Gliwice, Poland  
sergiusz.boron@polsl.pl*