# Power Distribution System Conductor Sizing as Viewed From Thermodynamics Principles

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1. Abstract

The task of educating members of an engineering team (engineers, engineering technologists, and engineering technicians) becomes even more challenging as technology evolves towards new horizons. Power electronics, robotics, networks, advances in manufacturing technologies as well as environmental and energy saving concerns call for new pedagogical and curriculum development approaches. Theoretical instructions, laboratory exercises, and projects should include emerging issues and be common to several disciplines across the curriculum.
One of the topics of such integration is identifying and linking related issues in electrical engineering/electrical engineering technology and thermodynamics courses.
An example of such a topic is sizing conductors based on their current carrying capacity as well as fault current calculations.

Power distribution systems for industrial facilities with voltages less than 1 kV are decisive in terms of systems' reliability, voltage quality, energy savings, and electromagnetic compatibility among others.
In such systems only fuses or automatic (molded case) circuit breakers are used to protect from overcurrents and faults unlike more sophisticated protection techniques in systems rated over 1 kV. Such thermal protection units have varying characteristics and could differ from unit to unit quite significantly. Therefore, conductors at this voltage level should be checked not only for rated continuous current carrying capacity (ampacity) but also for their thermal stability. Thermal stability calculations involve solving for conductors' temperature at the end of the fault clearing process. Maximum allowable temperatures depend on insulation properties and are defined by the National Electrical Code © (NEC) [1]

This paper derives formulas to determine time-current characteristics of conductors to be used in coordination studies related to protective devices. The results are used in corresponding energy courses (electrical and thermodynamics) as well as in student projects.

2. Conductor Selection Based on Short-Circuit Current Temperature Rise

According to the NEC® conductors are selected based on the following conditions:


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$$V_{nc} \geq V_n$$
$$I_{nc} \geq I_{act} K \qquad (1)$$

Where:
$V_{nc}$, $V_n$ - nominal cable voltage and substation voltage correspondingly, V;
$^2_{nc}$, $^2_{act}$ - conductor's ampacity and actual ampere rating respectively, A;
*Ê* – derating coefficient depending on actual temperature, number of conductors, etc.

Determination of conductor's thermal stability is based on its temperature at the end of a fault clearing process. Maximum allowable temperature during fault conditions depends on insulation properties and should not exceed 150$^0$C. To calculate actual temperature of cable insulation, the quantity of heat, which is being transferred from conductors to insulation, shell, and environment, should be determined over the time of protection action. Such calculations are very complicated, as they should involve varying temperatures as a function of varying fault current.
To simplify such calculations an adiabatic process of conductor heating is assumed.
Final temperature of the insulation is determined as:

$$\Theta_{fc} = \Theta_{ic} + \Delta\Theta , \qquad (2)$$

Where:
$Q_{fc}$ – final conductor's temperature, $^0$C;
$Q_{ic}$ - initial conductor's temperature, $^0$C;
*DQ* - temperature rise during short circuit, $^0$C

Depending on the insulation type, initial temperature is 75 $^0$C or 90 $^0$ and final temperature is 150 $^0$C.

Temperature rise is determined as:

$$\Delta\Theta = \frac{I_{sc}^2 R t}{C_p G} \qquad (3)$$

Where:
$I_{sc}$ – effective value of three-phase fault current's periodic component;
*R* – conductor's resistance, Ohm;
*t* – fault current duration, s;
$C_p$ – specific heat, J/kg*$^0$C;
G – conductor's mass, kg;

Since specific heat of conductors' material depends on the temperature, the value of specific heat is determined for conductor's initial temperature. Correspondingly, for aluminum $C_p$ = 932 J/kg*$^0$C and for copper $C_p$ = 390 J/kg*$^0$C.

Conductor's resistance at adiabatic process is found as:

$$R = R_{20} K_t , \qquad (4)$$

Where:


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$R_{20}$ – conductor's resistance at 20 ˆÑ, Ohm;
$\hat{E}_t$ – temperature coefficient of resistance

Since conductors are heated equally along the length of the cable the results of calculations would not depend on the length. Therefore the length could be considered as being 1m.

Then:

$$R_{20} = \frac{r_{20} l}{S} = \frac{r_{20}}{S} \quad (5)$$

Where:
$r$ - resistivity (for aluminum $r$ = 0.029 Ohm*mm/m and for copper $r$ = 0.0185 Ohm*mm/m);
S – cross-sectional area of the conductor, mm$^2$;
Than the mass of a 1m long conductor would be G = 0.002702*S for aluminum and G = 0.008933*S for copper.

Substituting (5) into (Ç):

$$\Delta\Theta = CK_t \frac{I_{sc}^2 t}{S^2}, \quad (6)$$

Where:
$\tilde{N}$ – a constant depending on specific heat and mass of a 1 m long conductor with cross-sectional area of 1 mm$^2$ (for aluminum $\tilde{N}$=0.01152 and for copper $\tilde{N}$=0.00531)

While calculating fault currents for circuits less than 1 kV an increase of conductor's resistance due to its heating by short circuit current should be considered. Therefore the value of R in (3) should correspond to an increased conductor's temperature.
To adjust resistance to this temperature the temperature coefficient of resistance $K_t$ should be used. Since the conductor's temperature varies linearly (adiabatic process) it could be determined as an average temperature during fault current interval:

$$\Theta_{avg} = \frac{\Theta_{c1} + \Theta_{c2}}{2}, \quad (7)$$

Where:
$Q_{avg}$ – average conductor temperature during short circuit, $^0$C;
$Q_{c1}$, $Q_{c2}$ – conductor's temperature at the beginning of the fault (75$^0$C) and maximum allowable temperature at the end of the fault, $^0$C.

Temperature coefficient of resistance with regards to (7) is:

$$K_t = 1 + a_{20}(\Theta_C - 20), \quad (8)$$

Where:
$a_{20}$ - a constant that depends on physical properties of conductor's material ( for aluminum $a_{20}$=0.00391 and for copper $a_{20}$=0.00393).

After simplifications:

$$K_t = a + b(\Theta_{c1} + \Theta_{c2}), \quad (9)$$

Where:
$a$, $b$ - constants (for aluminum $a$=0.9218, $b$=0.00196; for copper $a$=0.9214, $b$=0.00197).


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Fault current value could be expressed through its multiple of a protective device current tap setting (TS):

$$I_{sc} = KI_{cs} , \tag{10}$$

Where:

Ê – multiple of the fault current to TS;

$^{2}{}_{cs}$ – current tap setting (TS), A.

Substituting (9) and (10) into (6) and based on (2), the final expression for cable's insulation temperature is:

$$\Theta_{fc} = \Theta_{ic} + K_i \left( K \frac{I_{cs}}{S} \right)^2 t , \tag{11}$$

Where:

$\hat{E}_i$ – coefficient of initial conditions

$$K_i = a + b\left(\Theta_{c1} + \Theta_{c2}\right) , \tag{12}$$

Where:

*a* and *b* - constants (for aluminum $a$=0.01062, $b$=0.2258*10$^{-4}$; for copper $a$=0.0049, $b$=0.1046*10$^{-4}$).

The quantity of heat dissipated in a conductor depends on fault current duration or, in other words, on the clearing time. Since actual time-current curves of protective devices (circuit breakers and fuses) could differ significantly from unit to unit, calculation of the temperature rise during short circuit should be performed. In case time-current characteristics of protective devices are given as two curves, an algebraic average of fault clearing time should be used.

Based on (11) a time-current characteristic of a cable could be calculated when current tap setting of the protective device is set to conductor's ampacity ($I_{nc}$):

$$t_{cl} = \frac{\Theta_{c1} - \Theta_{c2}}{K_i \left( {KI_{nc}}/{S} \right)^2} , \tag{13}$$

Where:

$t_{cl}$ – maximum clearing time, s

It should be mentioned that time-current characteristics obtained by (13) are valid only for the assumed adiabatic process. It allows finding a guaranteed cable protection zone by comparing it with time-current curves of protective devices. For small multiples of fault currents to TS and relatively long clearing time the heating process will not be adiabatic and actual clearing time would be longer than calculated by (13).

3. Algorithm of Temperature/Clearing Time Calculations

1. Select initial temperature based on the insulation type $Q_{ic}$ ($75^0$C or $90^0$C for maximum cable loading)
2. Find coefficient of initial conditions $K_i$ based on (12)
3. Select a conductor and find conductor's ampacity $I_{nc}$ using the NEC tables
4. Determine protective device current tap setting $I_{cs}$


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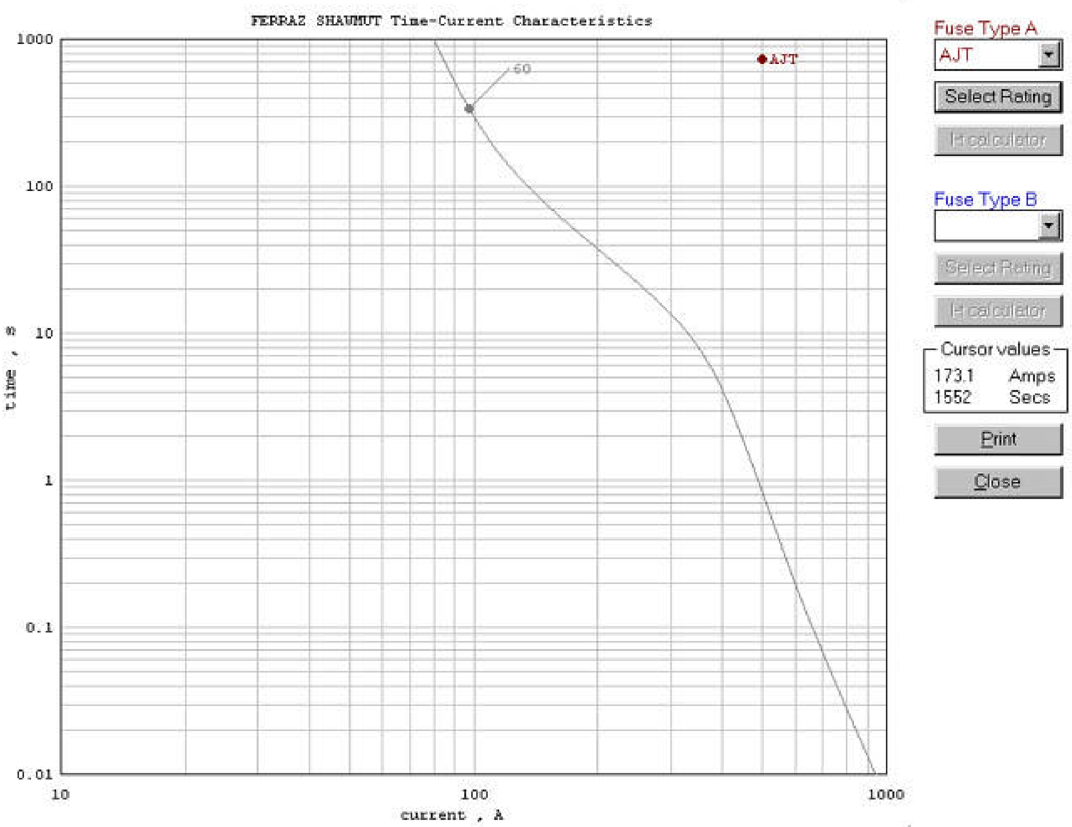
5. Determine multiple of the fault current to TS ($K = I_{sc}/I_{cs}$)
6. Find duration of the fault current based on the time-current curve of the protective device
7. Find final conductor's temperature $\Theta_{fc}$ using (11)
8. Determine minimal clearing time $t_1$ (if necessary) for protective device using (13)

Example.
Given:
3-phase motor, 460V, 30 hp (22.38 kW). Full motor load is 40A. Motor start time is 2.1 – 5s. The motor is protected by a fuse. Recommended fuse type is AJT60. For 40A full-load current #8 copper conductor (THHW) is selected (NEC, Table 310-16, cable with four conductors), with regards to four conductors in the cable, it's ampacity is 50 * 0.8 = 40A. Short-circuit current on the motor terminals to be cleared is 339A or 5.65 times of the fuse current setting. According to the fuse time-current curve [2] the clearing time is 9.4s.

Applying the proposed methodology, the temperature of the conductor would reach 186.95 $C^0$, which is more than 150$C^0$. The cable is not protected.

Stepping to a different cable size, such as #6 with ampacity of 65*0.8 = 52A yields the temperature of 119.3$C^0$, which satisfies the requirements.

Time-current curve for AJT60 fuse is presented in Figure 1.

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Mathcad calculations for AWG #8 conductor (corresponds to 8.366 $mm^2$) are presented below:

<u>Determination of conductor's thermal stability</u>
<u>Cable with copper conductors</u>

$a := 0.0049$

$b := 0.1046 \cdot 10^{-4}$

$\theta c1 := 75$

$\theta c2 := 150$

$S := 8.366$

(Cross-sectioanal area in $mm^2$)

$Inc := 52$

Inc - nominal ampacity, A

$Ics := 60$

Ics - current tap setting, A

$Isc := 339$

Ics - short-circuit current, A;

$K := \frac{Isc}{Ics}$

K - multiple of the short-circuit current to TS

$t := 9.4$ duration of the short-circuit current, s

$Ki(a, b, \theta c1, \theta c2) := a + b \cdot (\theta c1 + \theta c2)$

Ki - coefficient of initial conditions

$$\theta fc(Ki, Ics, S, K, t, a, b, \theta c1, \theta c2) := \theta c1 + Ki(a, b, \theta c1, \theta c2) \cdot \left(\frac{Ics \cdot K}{S}\right)^2 \cdot t$$

θfc - final conductor temperature, deg.C

$$\theta fc(Ki, Ics, S, K, t, a, b, \theta c1, \theta c2) \rightarrow 186.95387879512311738$$

$$tcl(Ki, Inc, S, K, t, \theta c1, \theta c2) := \frac{\theta c2 - \theta c1}{Ki(a, b, \theta c1, \theta c2) \cdot \left(\frac{Inc \cdot K}{S}\right)^2}$$

tcl - maximum clearing time, s

$$tcl(Ki, Inc, S, K, t, \theta c1, \theta c2) \rightarrow 8.3838941317369395995$$



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## 4. Conclusion

Calculations were be performed to verify if conductors are protected from short-circuit currents. As a result of numerous calculations it was determined that:

- Smaller conductors would overheat more than larger conductors during short-circuit
- At low multiples of fault current to a trip rating of protective devices, when clearing time according to the time-current curves is relatively long, the described methodology should be used to insure that the proper protection is utilized
- The methodology described in this article has been successfully used in a number of electrical and mechanical engineering/engineering technology projects at two institutions. At Buffalo State College Power Systems course incorporated it since fall semester of 2001. Sample syllabus is available through e-mail from grinbeiy@bscmail.buffalostate.edu. At L'viv Polytechnic National University the methodology has been used in Power Distribution Systems course from fall 2001. Projects incorporating the methodology have been done at both institutions. An example at Buffalo State was a student project done in fall 2001. The project incorporated feeder selection and coordination studies for several electrical loads at under 1 kV rating. Students were involved in developing programs to convert American Wire Gage (AWG) to metric system as well as in use of Mathcad to reach numerical solutions.

Bibliography

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