HOW FAR IS AN INSULATED CONDUCTOR PROTECTED BY A FUSE

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1. INTRODUCTION The I.E.C. rules regarding the protection of insulated conductors against overcurrent state as follows:

a) 433. Protection against overload current

433.1. Condition of application. Protective devices (in our case, Fuses) shall be provided to break any overload current before such a current could cause a temperature rise detrimental to insulation, etc.
433.2. Coordination between conductors and protecting devices. The operating characteristics of a device (Fuse) protecting a conductor against overload shall satisfy the following conditions:

$$I_B \leq I_n \leq I_z \qquad (1)$$

$$I_2 \leq 1.45\ I_z \qquad (2)$$

where:
I_B = Current for which the circuit is designed (B stands for Betriebstrom-V.D.E)
I_z = Continuous current carrying capacity of conductor. (z stands for Zulaessiger-strom - V.D.E)
I_n = Nominal current of the protective device. (in our case - rated current of Fuse)
I_2 = Current assuring effective operation of the protective device.

b) When the fuse has to protect the conductor against short circuit only, the I.E.C. rules are more specific and define the maximum permissible duration of the short circuit current until the conductor reaches a limit temperature depending upon the type of insulation. Such time is given, under assumption of adiabatic heating as:

$$t = \left(k \cdot \frac{S}{I} \right)^2 \qquad (3)$$

where:
t = duration in seconds
S = Cross sectinal area in mm^2
I = Short circuit current in A (R.M.S. value)
k = constant equal to 115 for copper conductors
The limit temperature for which k is calculated is 160°C for P.V.C insulation. Other values of k are given for different conductor materials and different types of insulation.

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It has to be pointed out that the assumption of adiabatic heating is nearly accurate only if it is of order of magnitude of a few seconds. For that the short circuit current must be quite strong. In the daily praxis, however, the short circuit current I may be such that will surely cause the Fuse operation, but in a time that may last for minutes instead of a few seconds. In such cases the conductor heating is very far from being adiabatic and Eq. 3 does not hold anymore. Nevertheless, practical engineers prefer to use Eq. 3, instead of embarking in more complicated calculations, because of:

a) Eq. 3 is simple and immediately applicable.
b) at first glance it seems that the time t calculated according to Eq. 3 always is on the safe side, because the assumption of adiabatic heating is far more severe than the real heating process in which the conductor looses heat due to its temperature rise.

A more accurate investigation of the heating process and the consequent deterioration of the insulating material, shows that the above mentioned simplified approach and its consequences may be unjustified and in very many cases lead to erroneous conclusions. The aim of this paper is to carry out such investigations and to show its logical consequences.

2. THE HEATING PROCESS Consider Fig. 1, representing an insolated conductor of cross sectional area of s mm^2.

Let:
R_o = the conductor resistance at surrounding temperature. [Ω]
α^o = the resistance coefficient related to surrounding temperature. [$1/^oC$]
h = the equivalent radiation constant, according to installation conditions. [$W/^oC.m^2$]
S = the cooling surface of the conductor. [m^2]
c = the specific heat of the conductor material. [$Ws/^oC.kg$]
G = the equivalent weight of the insulated conductor reduced to conductor material
Θ = the temperature rise upon the surrounding.

For the sake of concision, in the following, Θ shall be referred to as "temperature".

Supposing that a current of I Amp. flows through the conductor, the energy balance for an infinitesimal time dt, is:

$$R_o(1+\alpha\Theta)I^2 \cdot dt = hS\Theta\, dt + cG\, d\Theta \qquad (4)$$

Eq. 4 can easily be transformed into the following form:

$$\Theta'_\infty(1+\alpha\Theta)dt = \Theta\, dt + T\, d\Theta \qquad (5)$$

where:
$\Theta'_\infty = \frac{R_o I^2}{hS}$ is the temperature to which the conductor would settle after a long time if its resistance would stay constant at the value R_o, regardless of temperature increase.

$\frac{cG}{hS} = T$ (sec) is the "time constant" of the conductor, having different values for different instalation conditions, because of its dependence on h which changes with the varying conditions.

Solving Eq. 5, taking into consideration that at time t=0 the conductor temperature may be Θ_0 due to previous work, one gets:

$$\Theta = \frac{\Theta'_\infty}{1-\alpha\Theta'_\infty}\left[1 - e^{-\frac{1-\alpha\Theta'_\infty}{T}\cdot t}\right] + \Theta_0\, e^{-\frac{1-\alpha\Theta'_\infty}{T}\cdot t} \qquad (6)$$

which gives the conductor temperature as a function of time. Eq. 6 points out a very interesting fact. If $1-\alpha\Theta'_\infty > 0$ the exponential function decreases with increasing time, and the temperature asymptotically reaches the final value $\Theta_\infty = \frac{\Theta'_\infty}{1-\alpha\Theta'_\infty}$. If $1-\alpha\Theta'_\infty < 0$ the exponential is increasing with time, and the temperature steadily increases toward ∞ (Run away effect). See Fig. 2.

Let us suppose, for the moment, that the conductor is protected if the circuit is interrupted before its temperature reaches a maximal permissible value Θ_M (160°C for P.V.C). According to Fig. 2, the maximal permissible time t is given by the intersection point of $\Theta = f(t)$ with the line $\Theta = \Theta_M$. Mere observation of Fig. 2, discloses immediately that if $1-\alpha\Theta'_\infty > 0$, $t > t_a$, but if $1-\alpha\Theta'_\infty < 0$, $t < t_a$. Since t_a is the maximal permissible time by adiabatic heating, one may draw the first important consequence: if the conductor reaches the run away effect range, Eq. 3 gives values of time which <u>are not</u> on the safe side. It is important to observe that run away conditions are easily reached in current praxis. In order to check this point, let us reverse Eq. 6 getting the permissible time t as:

$$t = \frac{T}{1-\alpha\Theta'_\infty}\,\ell n\,\frac{1-(1-\alpha\Theta'_\infty)\,\frac{\Theta_0}{\Theta'_\infty}}{1-(1-\alpha\Theta'_\infty)\,\frac{\Theta_M}{\Theta'_\infty}} \qquad (7)$$

Let us now compare the values of t calculated using Eq. 7 with those calculated using Eq. 3. The results are given in Table 1 as a function of the relative short circuit current $j = \frac{I}{I_z}$, where I is the actual current and I_z as defined in the introduction.

Table 1 has been calculated for a copper conductor of $50mm^2$, having a continuous current carrying capacity of I_z=171 A and a time constant T=587sec. Table 1 clearly shows that any current larger than 5-6 times I_z starts a run away effect. For any current in this range Eq. 3 gives <u>excessive values</u> of t.

3. <u>DETERIORATION OF INSULATION</u> After having investigated the heating process, let us consider the deterioration of insulation caused by the temperature. It is a known fact that insulating materials loose their mechanical and electrical properties as well, with a speed rapidly increasing with the increase of conductor temperature. (Aging effect). In order to evaluate this effect, it is usual to define the Expected Life of the insulation (E.L. in the following) and to express its dependence upon temperature as:

$$E.L = A.e^{-\beta\Theta} \qquad (8)$$

where:
A = a constant having the dimension of time (generally years)
β = a coefficient giving the deterioration speed as a function of temperature. The dimensions of β are $1/^{o}C$.

Eq. (8) must be rightly understood. The definition of E.L. is "the time after which the insulation of 50% of a large number of new samples held at constant temperature Θ still preserve good insulating properties". One may look at this definition with a probabilistic approach, stating that the E.L. is the time span after which the probability of finding the insulation of a new conductor, held at constant temperature Θ, in good conditions of insulation still, is 50%. This definition avoids a common misinterpretation of the E.L. concept. The E.L. does not define a time span after which the conductor insulation is surely destroyed. A conductor actually can be used for a time much longer than its E.L. without any fault of insulation, but its reliability is strongly affected because the probability of being in good condition becomes smaller and smaller with increasing time. Basing on Eq. 8 it is possible to evaluate the damage done to the conductor insulation by a short circuit.

Let us assume that a conductor is held at constant temperature equal to the permitted one Θ_z. Eq. 8 applied to this case will give an expected life which may be defined as "rated expected life". (R.E.L) If the conductor is at temperature $\Theta \neq \Theta_z$ its expected life will be E.L. $\neq$ R.E.L. Assuming that such situation lasts for a time Δt, the relative loss of expected life will be:

$$\Delta E.L = \frac{\Delta t}{E.L} \tag{9}$$

In order to cause the same relative loss of expected life at temperature Θ_z a time $\Delta t'$ will be necessary, which satisfies

$$\frac{\Delta t'}{R.E.L} = \frac{\Delta t}{E.L} \tag{10}$$

$$\Delta t' = \frac{\Delta t \; R.E.L}{E.L} \tag{11}$$

Putting instead of R.E.L and E.L their expressions as per Eq. (8) one gets:

$$\Delta t' = \Delta t \; e^{\beta(\Theta - \Theta_z)} \tag{12}$$

Expressing $\Delta t'$ in percents of the R.E.L one gets:

$$D.F = \frac{\Delta t \; e^{\beta(\Theta-\Theta_z)}}{R.E.L} 100\% = \frac{\Delta t e^{\beta\Theta}}{A} 100\% \tag{13}$$

Such expression may be considered as deterioration factor D.F. giving how many percents of the R.E.L are lost, due to a temperature Θ lasting for a time Δt.

During a short circuit the conductor temperature rises from the initial temperature Θ_o to the maximal one Θ_M at the moment of current rupture by the Fuse. After this moment the conductor begins to cool down. The temperature during the heating period is given by Eq. (6). During the cooling period the temperature behaves also according to Eq. (6) where $\Theta'_\infty = 0$ and $\Theta_o = \Theta_M$. Therefore, for the cooling process:

$$\Theta = \Theta_M \; e^{-t/T} \tag{14}$$

Since the insulation deterioration depends on the temperature, regardless of its source, one realizes that there are two deterioration factors:
a) The prearcing deterioration factor (P.D.F) due to the heating period.
b) The "after deterioration factor" (A.D.F) due to the cooling period.
The total deterioration factor will be:

$$D.F = P.D.F + A.D.F \tag{15}$$

There is no difficulty to calculate both P.D.F and A.D.F. The prearcing time t is given by Eq. (7). The temperature at any time is given by Eqs. (6) and (14) respectively. Thus one gets immediately:

$$P.D.F = \frac{100}{A}\int_{o}^{t} e^{\beta\left[\frac{\Theta'_\infty}{1-\alpha\Theta'_\infty}\left(1-e^{-\frac{1-\alpha\Theta'_\infty}{T}\cdot t}\right)+\Theta_o e^{-\frac{1-\alpha\Theta_\infty}{T}t}+\Theta_s\right]} dt \quad \% \tag{16}$$

and

$$A.D.F = \frac{100}{A}\int_{o}^{t_i} e^{\beta(\Theta_M e^{-\frac{t}{T}}+\Theta_s)} dt \quad \% \tag{17}$$

Both integrals are easily solved by numerical integration. For that a common programmable desk calculator is sufficient.

The integral of Eq. (17) presents a little difficulty in evaluating the integration time t_i. Such difficulty is avoided stopping the integration when the temperature reaches again the value Θ_o. Any prolongation will add to the integral a negligible contribution. Θ_s appearing in Eqs. (16) and (17) is the surrounding temperature, which is added to the calculated one because the insulation deterioration is due to the real temperature of the conductor, not by its temperature rise over its surroundings.

The author wishes to point out that the D.F. gives only an indication of the severity of the injury done to the insulation by a short circuit, not an exact calculation, because in real life things are more complicated. A conductor never carries a constant current. There are periods of heavy load, periods of reduced load and periods of no load. Thus the starting temperature is different in any case. Eq. (16) and (17) take into consideration the worst possible situation.

The following Table 2 shows the P.D.F and the A.D.F of various copper conductors, calculated for the worst case in which the starting temperature is 70°C and the maximal permitted temperature is 160°C. In order to ease comparison P.D.F and A.D.F are given in thousandths of percent.

Considering Table 2 one may observe many important facts:
a) The A.D.F obviously is independent from the relative short circuit current j, but is strongly dependent on the conductor cross section s. For instance by any j, the A.D.F changes from 0.402% for $s=25mm^2$ to 3.182% for $s=240mm^2$, being all other conditions equal.
b) The P.D.F depends on both s and j.
c) The contribution of the P.D.F to the total deterioration factor becomes more and more heavy when j decreases.
d) The logical consequence is that from point of view of insulation deterioration the most dangerous overcurrents are those which exceed the conductor rated current by a factor changing from 1 to 3.

In order to emphasize this point Table 3 has been worked out. In this Table the total D.F. has been calculated for a conductor of 240mm^2 for j=1.6 to j=15. In line 1 are given the results assuming that the conductor is allowed to reach in any case the maximal temperature of 160^{o}C. Line 2 gives the pertinent heating time from 70^{o}C to 160^{o}C. Line 3 gives the maximal temperature reached when the conductor is allowed to heat up until the D.F reaches the limit of 1%. Line 4 gives the heating time in this case. Table 3 enables more useful observations:

e) For heavy conductors the maximal temperature limitation criterion may lead to unacceptable heavy D.F. For instance by j=1.6 the conductor will loose more than 17% of its rated expected life until it reaches 160^{o}C.
f) Limiting the maximum permitted D.F., instead of temperature, the maximal temperature will decrease with decreasing j.

Observations e) and f) do not exclude the use of Eq. (3) or a similar one. The necessary change will be that factor k will no longer be constant, but a function of conductor size, its instalation conditions and j. Such functions can be given in tabulated form.

Starting from completely different considerations the V.D.E people came to a similar conclusion, recommending that for conductors of cross section exceeding 150mm^2 the limit temperature shall be reduced to 130^{o}C. After these considerations it is possible to answer the question posed in the heading of this paper: How far does a Fuse protect a conductor? Consider first the case that the rated current of Fuse and conductor are equal. $I_n = I_z$. In such case there is no doubt that for j>3, the conductor is fully protected because the fuse operating time is much shorter than the permitted heating time in both cases of temperature and D.F limitation. For j<3, the situation is more problematic. A Fuse of size 4, which corresponds to the rated current of a conductor of 240mm^2 shall not interrupt during the test period for j=1.3, and shall interrupt within such period for j=1.6. The test period in this case is three hours. That means that by j=1.6 the Fuse can delay its action up to 10800 seconds still being in accordance with the regulations.

Comparing this time with that given in Table 3, line 4, one realizes that the conductor insulation may be severely deteriorated until the fuse reaction occurs. This behavior is mainly due to the "indifference gap" pertinent to any fuse. There is a specific value of $j=j_s$ which divides the infinite field of j into two zones. The unprotected zone for $j<j_s$ and the protected zone for $j>j_s$. The width of the unprotected zone depends upon the conductor cross section and the fuse rated current as well. Wishing to protect the conductor from j=1 to infinity one has to choose a fuse of rated current much smaller than I_z thus wasting expensive active material. Moreover, in specific cases the regulations allow to protect a conductor with a fuse of rated current larger than I_z. In such cases the unprotected zone can be considerably wide, thus enlarging the span of dangerous currents.

3. CONCLUSIONS

1) In the author's opinion the criterion of maximum permissible temperature should be replaced by that of maximum permitted D.F.

2) The regulations make a distinction between "overload currents" and "short circuit currents", differentiating them with regard to their origin. (Overload if due to excessive load or mechanical faults, short circuit if due to fault of electrical nature). These definitions, and other proposed

ones do not lead to calculatable values, thus leaving the possibility of overlapping or separation between the two ranges. The author suggests to choose j_s as separation point between overload and short circuit currents.

3) Basing on the above mentioned distinction the regulations consider separate protections against overload and short circuit. In many cases the regulations allow to protect a conductor against short circuit only. In such cases it is permitted to protect the conductor by a fuse of $I_n > I_z$. Though such arrangement generally works, it is conceptually not sound. One is able to calculate the maximal short circuit current, but nobody can predict the minimal one, which depends upon the more or less random impedance of the short circuit itself. Especially when $I_n > I_z$ a relatively small impedance can reduce the current into the unprotected zone. By fuse protection there is no completely satisfactory solution of this problem.

4) For the same reason the requirement that the interruption time shall be less than 5 seconds, is illusoric. Any possible short circuit impedance can reduce the current enough to cause a reaction time greater than 5 seconds. On the other hand, a conductor can support the short circuit current for more than 5 seconds without excessive deterioration.

5) Speaking of heavy expensive circuits the ideal protection may be offered by a semiconductor device, rather than by a fuse. Such semiconductor device shall sense both the current and the conductor temperature. It shall include an integrating circuit which starts to calculate the P.D.F when the current exceeds I_z. If the P.D.F reaches a preset limit, the current shall be cut off, until a manual reset. Such device may also include a time element which limits the reaction time to 5 seconds if required.

As a last remark, the author does not suggest any particular value for the maximum permitted D.F. Such a suggestion shall be the result of a team work which would consider both technical and economical considerations as well.

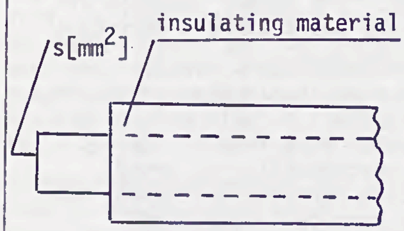

Fig. 1 - Insulated Conductor

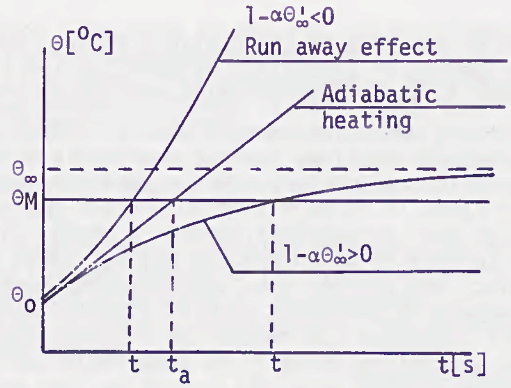

Fig. 2 - $\Theta = f(t)$

j	2	3	4	6	8	10	12	14	16	18	20
t(Eq.7)[s]	624	156	77	31.26	17.09	10.79	7.44	5.45	4.16	3.28	2.65
t(Eq.3)[s]	283	126	71	31.41	17.67	11.31	7.85	5.77	4.42	3.49	2.83

Table 1 - t(Eq.7) versus t(Eq.3)

j / s	3		6		9		12		15	
mm^2	PDF	ADF	PDF	ADF	PDF	ADF	PDF	ADF	PDF	ADF
25	104	402	20	402	9	402	6	402	3.5	402
50	203	807	49	807	17	807	11	807	7	807
95	361	1347	66	1347	29	1347	17	1347	11	1347
150	525	2120	104	2120	45	2120	27	2120	17	2120
240	787	3182	156	3182	67	3182	41	3182	26	3182

Table 2 - P.D.F and A.D.F given in % x 10^{3}

	Relative short circuit current j	1.6	2	2.5	3	6	9	12	15
1	DF (%) limit temp. 160°C	17.28	6.52	4.72	3.97	3.34	3.25	3.22	3.21
2	Heating time (s) to 160°C	3870	1367	699	436	93	41	23	19.48
3	Max temp. (°C) by DF=1%	141	147	149	149	150	151	151	151
4	Heating time (s) for DF=1%	2650	1148	615	384	84	37	21	13

Table 3 - Comparison between max temp. and max DF