PERMANENT DESIGN OF POWER SYSTEMS. THE CURRENT IMPULSE: A CHARACTERISTIC PARAMETER

G. Parise (L. Fellow IEEE)
Civil&Industrial Engineering Faculty Sapienza University of Rome, Italy
parise@ieee.org

Abstract. The design of an electrical system is permanent and a complex process that must follow the system throughout its complete life. All system components, from the installation and commissioning, are subject to a natural degradation which will lead to deterioration of the electrical and mechanical properties, leading to the end of its life. Therefore, the electrical system, to guarantee a "nominal" performance within an assigned period of time, must be monitored and managed in actual operation. The operation of each component in anomalous conditions occurs if it is affected by an overcurrent. Consequently, overcurrents must be taken into consideration and counted as increases in the natural "loss" of life. In correlation with each overcurrent event, the increase in natural aging can be evaluated. A procedure based on the Arrhenius model of the thermal aging of insulating materials allows to introduce the relative time coefficient (RTC) which evaluates the aging rate variation and to promote a simplified method for an estimate of the loss of life and the residual useful life of insulated electrical cables. As well known, in the case of transient - adiabatic events such as short circuits, the circuit conductors must be affected by a let-through energy not exceeding a specific energy tolerable value. This paper highlights how the conductor's behavior can also be characterized analyzing the parameter impulse of current tolerable for the conductors.

Key words: Operation, Maintenance, Arrhenius Model, Electric Power Cables, Design Criteria

SYMBOLS

a, b	Arrhenius parameters of the insulating materials
D, D_n	lifetime in [h] and nominal lifetime of about 175,200 hours (20 years) at T_z of an insulated cable [h]
I_{bc}	rated short circuit breaking capacity of protective device
I_f	conventional functioning current for overloads
I_k	prospective short circuit current- tolerable impulse current
$I_{k,1s}$	impulse current for 1s, value coincident with current impulse
$I_k^2\,t$	let-through energy of protective device [A^2s]
$I_k\,t$	impulse of current of prospective short circuit [As]
I_m	tripping setting current, instantaneous or slightly delayed
I_n	rated current of the protective device
I_z	cable current-carrying capacity
K^2S^2	tolerable let-through energy (IEC) for a conductor S
K	IEC constant value [$As^{1/2}/mm^2$], current density - impulse density threshold value referred to events of t=1 s
LE	life efficiency of insulated cable
LL(t)	life loss cumulated from t_0 of an insulated cable (age of insulated cable) [h]
LLR	life loss rate of an insulated cable [h]
RL(t)	nominal residual life of an insulated cable [h]
RTC	relative time coefficient [h/h] at T_e, aging speed of insulated power cable in t: note that at T_Z, RTC =1 natural speed
S	cable cross-sectional area in mm^2
t	event duration time [s] (computed in h for LL) or fault clearing time of the protection device
t_0	operating time lived before the event in consideration [h]
t_0+t	total operating time of a circuit including the event [h]
$\sqrt{t}$	impulse factor [$s^{1/2}$]
T_e	cable effective temperature
T_i, T_f	initial and final temperatures
T_k	tolerable short circuit temperature
T_z	maximum cable operating temperature

I. INTRODUCTION

The design of an electrical system is permanent and has to be understood as a complex process that must follow the system throughout its complete life. It essentially consists of two fundamental phases [1]. The first design phase of an electrical system is that of its conception which must refer to the standards of the art's rule or best practices. In fact, the standards provide the general criteria for a presumed correct configuration of the system in relation to the more general case of reference. Therefore, the designer must implement and adapt the objectives and general criteria/guidelines to the specific case of the system, must carry out its installation and commissioning. The next design phase is that of managing the system operation, adapting it to new possible needs and monitoring the lifetime of the system components. In fact, the management has real data on actual operation to be compared with the preliminary prospected data applied in the first phase and so, useful for necessary corrective measures and possible modifications. This operational planning phase is relevant as a tool for implementing interventions that satisfy the pre-established objectives/directions and are adapted to new needs and the implementation of energy and sustainability strategies. Furthermore, a process of normal deterioration of equipment is normal and can cause faults or an anomalous operation if it remains uncontrolled. Therefore, operation programs of preventive maintenance have to preserve the efficiency and the performances of the various components of the power system. At this aim, the system operating has to be continuously checked to evaluate the safety and reliability at least of the main components. Control systems consent to measure and record important parameters that allow concur to assess the status check of the components such as the aging of cables. Moreover, the operation of electrical systems is currently assisted by very efficient software, but its manager needs to know thumb rules and practical criteria to maintain a full understanding of the strategies to follow to achieve the objectives. An optimized management of the commercial and industrial energy system must take care of the actual operational and energetic strategy of the electrical system.

A procedure based on the Arrhenius model [2] of thermal aging of insulating materials allows introducing the relative time coefficient (RTC) [3] and promoting a simplified method for estimating the loss of life and residual useful life of the system components. In particular for insulated power cables,

the proposed method allows to synthetically diagnose the loss of life and residual useful life of insulated power cables and allows to organize an algorithm to count the “hours of loss of life” at least for power cables LV of the main/critical circuits.
For this purpose, for short circuit events that stress the circuit cables for very short times (adiabatic events), this paper deems it useful to identify the current impulse as a constant parameter that characterizes the insulated power cables whose quadratic value corresponds to the conventional value of tolerated let-through energy.

II. THERMAL AGING OF CIRCUITS

Each component of the system and in particular the cables must perform their "nominal" function, guaranteeing a defined performance within an assigned period of time. Therefore, from the moment an electrical component is installed and commissioned, it is subject to a natural degradation process which will lead to deterioration of the electrical and mechanical properties of the component itself, leading to its end of life. The aging of materials is due to the stresses they must withstand. Stresses that are of various nature: electrical, thermal, mechanical and due to atmospheric agents.
Among these, electrical and thermal ones are always present and it is their size that determines, in most cases, the lifetime of the insulation also because the presence of armor and/or sheaths ensures protection from mechanical and physical stress.
In cables used in low voltage electrical systems, the threshold dielectric gradient value is never exceeded, because the cables are insulated with materials with thicknesses far greater than those necessary to ensure dielectric strength and mechanical robustness. The rate of degradation, therefore, is essentially a function of the temperature of the insulation: the thermal aging. A procedure based on the Arrhenius model of the thermal aging of insulating materials allows introducing the relative time coefficient (RTC) which evaluates the variation in aging speed compared to the clock time [h/h] and to promote a simplified method for estimating the loss of life and the residual useful life of insulated electrical cables. The Arrhenius model is covered by the international standard [2] and for which the characteristic parameters of a significant number of insulators are available in the literature. The Arrhenius thermal aging model can be summarized by the well-known expression:

$$\log_{10} D(T) = a + \frac{b}{T+273} \qquad (1)$$

Where:

- D is the expected lifetime [h] at the temperature T[°C];
- a, b are two characteristic parameters of the insulating material (Table I).

Having set a plausible expected lifetime for the cables (D_n= 20 years – 175,200 h), the operating temperature T_z of the cable is obtained

$$T_z = \frac{b}{\log_{10} D_n + a} - 273 \qquad (2)$$

For the most common materials it applies, for PVC T_z = 70-75 °C, for EPR T_z = 90 °C (Table II) [8, 9, 10].
Therefore, the current-carrying capacity (ampacity) I_z of an electric cable is the current for which, under specified conditions and at the reference ambient temperature, the cable assumes the value T_z as its operating temperature.
Consequently, the cable will have a useful life equal to the expected one (175,200 h) in the theoretical case in which the insulation temperature remains constantly equal to the expected operating temperature T_z.
Operation of a distribution system in anomalous conditions occurs every time that part of the system is affected by an overcurrent, i.e. a current greater than its operating value I_z for unforeseen durations.
Overcurrents are divided into overloads and short circuits depending on whether the overcurrent occurs in a healthy circuit that is overloaded or in a circuit affected by a fault that causes short circuit.
However well designed and well operated a system may be, it should be noted that overcurrents cannot be prevented, quite in some cases overloads must somehow be tolerated within defined limits, to guarantee the service continuity.
The main effect of overcurrents is the increase in temperatures of the active parts of the circuit compared to normal operating conditions and therefore producing an anomalous and unplanned aging. In the case of low voltage systems, it is essentially the thermal stresses that cause the aging of the components.
Therefore, considering a controlled increase in the aging of the component as a parameter of admissibility of overcurrents, it can be concluded that the effective operation permitted in anomalous conditions occurs in the case in which the event causes a stress (temperature over time) not exceeding that tolerated.
Thus, unavoidable overcurrents must be taken into consideration and counted as life losses, i.e. calculating the actual duration of the event in a weighted manner with respect to natural aging.

TABLE I: ARRHENIUS EQUATION PARAMETERS FOR EPR, PVC, XLPE [4]

Material	Property	a	b	T_Z [°C]	D_n [years]	Ref.
EPR	t.s.	-11.627	6127	90	20.4	[5]
	v.b.	-11.913	6247	90	22.6	[5]
	e.b.	-11.918	5514	45	30.1	[6]
PVC	t.s.	-13.194	6324.2	70	20.0	[1,3]
	v.b.	-12.505	6225	75	27.6	[7]
	e.b.	-11.242	5704	70	27.9	[7]
XLPE	v.b.	-10.403	5502	80	17.4	[5]
	e.b.	-11.109	5782	80	21.3	[5]

Reference properties are: tensile strength (t.s.), loss of mass (l.m.), elongation at break (e.b.), voltage breakdown (v.b.).

TABLE II. RTC VALUES FOR EPR AND PVC CABLES

I_e/I_Z [%]	PVC(ts) T_Z=70°C		EPR(ts) T_Z=90°C	
	T_e [°C]	RTC [h/h]	T_e [°C]	RTC [h/h]
80	**55.6**	**0.17**	**68.4**	**0.09**
90	**62.4**	**0.42**	**78.6**	**0.28**
100	**70.0**	**1.00**	**90.0**	**1.00**
110	**78.4**	**2.50**	**102.6**	**3.68**

In practice, the parameter to manage and control overcurrent phenomena is to establish the percentage of the cable insulation lifetime that can be sacrificed to cope comprehensively with overcurrents (e.g. a life loss of 10%), while the main lifetime remains aimed to normal service (as already mentioned, at temperature T_z the global lifetime is conventionally assumed for the cables is 175,200 h).
For example, if each overcurrent event could cause an allowable life loss rate LLR equal to approximately 1/1000, each event corresponds to an allowable duration for which the predetermined loss of life occurs.
It is therefore established that 100 overcurrent phenomena are permissible each with a life loss up to the limit value 1/1000. Remembering that it is always desirable not to have overcurrent phenomena, the overall number of short circuits and overloads is in any case linked to the conventional share of overall loss of life of 10%.
A useful parameter is introduced for the purposes of conventionally evaluating the life losses: the RTC (relative time coefficient) aging speed.
Assuming that for the reference operating condition of a circuit at nominal ampacity I_z, the aging speed RTC is that expected as natural and so equal to RTC=1 at T_z, that is one hour chronologically elapsed by the cable is equivalent to one hour of life actually lost compared to the conventional life of 175,200 h.
In each monitored time interval t, the effective temperature T_e assumed by the circuit cable is correlated to the effective current I_e generally different from the ampacity I_z and can be evaluated adopting the simplified equation [11]:

$$T_e = \left(T_Z - T_a\right)\frac{I_e^{\ 2}}{I_Z^{\ 2}} + T_a \qquad (3)$$

where T_a is the reference ambient temperature and I_Z the related ampacity.
Therefore, in relation to the effective cable temperature T_e, the aging rate (RTC) of the cable, in relative value, is defined as the ratio between the lifetime at the temperature T_e and the conventional lifetime at the temperature T_z. If the cable temperature T_e goes above or below the operating temperature T_z, its RTC will increase or respectively decrease as a function of the aforementioned Arrhenius law.
A reworking of the law provides a convenient expression of the rate of aging:

$$\log_{10}\left[RTC\left(T_e\right)\right] = \frac{b\cdot\left(T_e - T_z\right)}{\left(T_e+273\right)\cdot\left(T_z+273\right)} \qquad (4)$$

Where:
- RTC is the relative aging speed [h/h], compared to the unit speed that occurs when the cable temperature is equal to the operating temperature T_z,
- b is an Arrhenius parameter whose value is known in the literature for various insulating materials (Table I),
- T_e [°C] is the effective temperature of the cable.
Considering a time interval t lived at temperature T_e, the loss of life suffered by the cable in h is equal to:

$$LLR(t)=RTC(T_e)\times t \qquad (5)$$

It is clear that LLR becomes sensitive when T_e is much higher than T_z and for a time duration t [h] likely for overloads.
Therefore, the overall lifetime $LL(t_0+t)$ considers the experienced LLR by the cable since the installation time t_0 until the start of the event of duration t and the updated LLR by the same event and so, is defined by:

$$LL(t_0+t) = LL(t_0)+RTC(T_e)\times t \qquad (6)$$

In practice, it constitutes the algorithm for an hour counter of life loss that allows to monitor the LV power cables, at least of the main/critical circuits. The life efficiency LE of the power cable remains defined by the relationship

$$LE = \frac{LL(t_0+t)}{(t_0+t)} \qquad (7)$$

that characterizes:
- a quantitative index of cable exploitation,
- the average aging speeds.

Knowledge of the LE ratio allows the operation of the controlled system circuits based on real and non-estimated parameters; in particular, allows to increase/decrease the load that can be powered by the circuit, satisfying new user needs, to allow temporary overloads or adjustments to the system configuration, to redefine the protection calibration.
For the PVC and EPR cables the table II shows the values assumed by the effective temperature T_e in relation to four values of the load current ratio I_e/I_Z (3) and the RTC values estimated by the (4) the ratio adopting the related b parameters shown for tensile strength t.s. .
The residual nominal life RL of the cable remains defined by the relationship

$$RL(t)=D_n - LL(t_0+t) \qquad (8)$$

represents still available in reference to the expected life (D_n). It is certainly more important to be able to evaluate the years remaining of life rather than those already lived.
In conclusion, the method proposed in evaluating $LL(t_0+t)$ allows to synthetically diagnose the loss of life and the residual useful life of insulated electrical cables and as already mentioned, allows to organize an algorithm to an "hour counter of life loss" for the LV power cables at least of the main/critical circuits [12].

III. THE PROTECTION AND COORDINATION

The evaluation of short circuit currents in an electricity distribution system is fundamental for correct design and adequate coordination of protections.

Once the presumable overcurrents in a circuit have been defined, a suitable device must be provided for its protection. The problem of coordination between protection and circuits in practice is faced and solved with:

- the careful choice, among the protection devices available on the market, of the one that has the most suitable characteristics (when it is not possible to adjust them appropriately) to fulfill the pre-established protection task,
- the possible modification of the characteristics of the circuit (such as for example the conductor section S), i.e. adapting in a tolerable way the expected overcurrents to the available protection device.

The criteria of protection and coordination consider:

- for overloads, the tolerable value for the cables in a conventional time (1.45 I_z in IEC approach),
- for short circuits, the two extreme short circuit values, respectively minimum value I_{kmin} and maximum value I_{kmax} characterizing the circuit, as well as the values of specific let-through energies that the protective device lets permit in correspondence with the two short-circuit values.

Then, at the aim of the coordination, for the overloads, a protection device is characterized by the conventional functioning current I_f.

For the short circuits, a protection device is characterized by the minimum tripping current I_m, by the breaking capacity I_{bc}, by the breaking durations t in correspondence with I_m and I_{bc}, by the value of the rated current I_n for the continuous service.

Given that a short circuit can occur at any point of a circuit, the protection has to be provided at the same installation point of the circuit.

In synthesis, the coordination of circuit protection essentially consists in the adoption of a protective device which has [13,14]:

- a conventional functioning current I_f lower no-higher than the tolerable overload in the conventional time (in IEC approach, $I_f \leq 1.45\ I_z$),
- a breaking capacity I_{bc} higher than the maximum prospective short-circuit current I_{kmax} at the point of installation ($I_{kmax} \leq I_{bc}$),
- a timely tripping for the minimum distant short-circuit current I_{kmin} ($I_m \leq I_{kmin}$),
- let-through specific energies, in correspondence with the I_{kmax} and I_{kmin}, no-higher than the I_k^2t value tolerated by the cable adopted for the circuit.

Now, applying the coordination criteria stated to the two types of protection devices, automatic switch and fuse, it can be observed that in the case of the circuit breakers, since its tripping is established by the threshold value I_m, the distant short circuit is protected in a local way if the I_m value is less than I_{kmin}, as already noted.

For an automatic circuit breaker, the tripping time is generally constant for all currents higher than the I_m, therefore, the let-through specific energy increases as the short-circuit current rises and the maximum let-through specific energy corresponds to the maximum short-circuit value I_{kmax}.

If the condition $I_{kmin} > I_m$ is not respected, it is necessary to check the thermal resistance even for the minimum short circuit.

Otherwise, the intervention curve of a fuse, due to its behavior as a short-circuit current limiter, is that it limits a lower specific let-through energy as the short-circuit current increases.

IV. THE CURRENT IMPULSE TOLERABLE FOR A CABLE

As well known, the flow of the high currents that characterize short circuit faults must be promptly interrupted to avoid inadmissible heat developments in the conductors and the reaching of unacceptable high temperatures. Therefore, the short circuit currents I_k, correctly protected, must remain very short events with tolerable let-through energies and with correlated values of current impulse I_k t. In adiabatic event, the heat produced by the high currents remains totally absorbed by the conductor itself and must not exceed defined admissible values T_k of temperature (Table III). The IEC approach considers as adiabatic an event of duration up to 5s, the ICEA approach up to 10s.The lack of heat dispersion in event of adiabatic time t determines a homogeneous behavior of every part of the section S of a conductor which fills the energy storage capacity of the same conductor.

On the contrary, the dispersion of the heat determines a non-homogeneous behavior of the section S of a conductor between the central parts and the edges and establishes a permissible stationary condition of current conduction. In synthesis, the flow of a short circuit current in a conductor is limited to be an adiabatic event, because it develops heat totally absorbed by the conductor itself. The tolerable transient-high temperature T_k for each kind of conductor limits the specific energy I_k^2t to a specific value, threshold of the energy storage capacity of the same conductor and current conduction is limited to an impulse I_kt.

Therefore, cable conductors present a characteristic behavior, characterized by a specific current I_k tolerated for each t duration and so by a correlated current impulse I_kt.

For a conductor of section S in mm^2, the tolerable specific energy I_k^2t [A^2s] for an adiabatic event is conventionally calculable as [14, 15]

- for copper (Cu) cables

$$I_k{}^2t = 117612 \log_{10} [(T_k + 234.5) / (T_z + 234.5)] S^2 \quad (9)$$

TABLE III. TEMPERATURE LIMIT VALUES [14, 15]

Maximum Admissible Temperatures of Power Cables				
Temperatures $T_{z,k}$ (°C)	**Operating T_z (°C)**		**Shortcircuit T_k (°C)**	
Insulation Kind	**IEC**	**ANSI/ IEEE**	**IEC**	**ANSI/ IEEE**
Ethylene–Propylene EPR	**90**	***90***	***250***	***250***
Polyvinyl-Chloride PVC	**70**	***75-90***	***160***	***150***
Silicon Rubber	**180**	***125***	***350***	***250***

- for aluminum (Al) cables

$$I_k^2 t = 49500 \log_{10} [(T_k + 228) / (T_z + 228)] S^2 \quad (10)$$

In the expressions, T_k is the upper limit of the temperature in °C, T_z is the initial value of the temperature in °C, conventionally allowed for the type of cable (Table III).

The International Electrotechnical Commission IEC [13] defines the second term of (9) and (10) introducing a constant value K [$As^{1/2}/mm^2$] (Table IV) dependent on the type of material (Cu, Al) and proportional to the section S of the conductors:

$$I_k^2 t = K^2 S^2 \quad (11)$$

This constant threshold value K^2S^2 expresses the tolerable specific energy that transfer electrical energy in the heat completely stored by the conductor of section S.

It is known that 1 ampere or coulomb/second [A=C/s] corresponds to an impulse of current (charge) of one coulomb flowed through a conductor in 1 second and so a current value I_k [A] related to a 1s is evidently coincident with an impulse value I_k t [C]. Therefore, for an adiabatic event of t=1s, the expression (11) allows to identify the two reference parameters, the tolerable current $I_{k,1s}$ coincident with the tolerable impulse and so the impulse density $I_{k,1s}$ /S

$$I_k \sqrt{t} = KS \equiv I_{k,1s} \quad (12)$$

$$I_k \sqrt{t}/S = K \equiv I_{k,1s}/S \quad (13)$$

Therefore, the IEC constant value K corresponds for t=1s to the tolerable current density coincident to the tolerable impulse density [16].

This paper points out how to the specific energy K^2S^2 allows identifying the impulse current $I_k(t)$ value and the impulse current density $I_k(t)/S$, tolerated in a time t in relation to the values tolerated in 1s, $I_{k,1s}$ and $I_{k,1s}/S$

$$I_k(t) = I_{k,1s}/\sqrt{t} = KS/\sqrt{t} \quad (14)$$

$$I_k(t)/S = K/\sqrt{t} \quad (15)$$

Let us note that √t, the square root of t, has to be identified as an impulse factor that restores the value of the current tolerated in 1s to the value tolerated in t time. For instance, considering the K=143 related to EPR cables and a tripping time t equal to a cycle, 0.02 s at 50Hz and 0,0167s at 60 Hz, the tolerated current density I_k/S is equal to $K/\sqrt{t}$ =1011 and 1108 A/mm^2 respectively by the (15).

Then, adopting the impulse factor √t, the impulse I_k t of the current tolerated in the time t and so the tolerable impulse density $I_k t/S$ are defined in relation to the corresponding values tolerated in 1s

$$I_k t = I_{k,1s} \sqrt{t} = KS \sqrt{t} \quad (16)$$

$$I_k t/S = I_{k,1s} \sqrt{t} / S = K\sqrt{t} \quad (17)$$

Therefore, it can be noted that for event durations of less than 1 s, the tolerable impulse of current KS √t takes on a greater value the shorter the duration t, so that the conductor, thanks to its thermal inertia, reaches the tolerable temperature T_k in

TABLE IV. IEC VALUES OF K

t=1s	K (T_f, T_i) [$As^{1/2}/mm^2 \equiv C/mm^2$]		
T (°C)	Final		
	160	250	350
Initial	Copper		
90	*100*	*143*	*173*
70	*115*	*154*	*183*
	Aluminum		
90	*65*	*94*	*113*
70	*75*	*101*	*119*

the short time t, always with the same constant value of the tolerated specific energy $I_k^2 t = (KS/\sqrt{t})^2 t = K^2S^2$.

In synthesis, the knowledge of K and KS allows to define:

- the tolerated impulse current $I_k(t)$ and the $I_k(t)/S$ density respectively multiplying the values K and KS by $1/\sqrt{t}$
- the current impulse $I_k(t)t$ and the $I_k(t)t/S$ density respectively multiplying the values K and KS by √t.

At the aim of the protection coordination of the circuit, the designer calculates the actual short circuit value I_k and prospects the tripping time t of the protective device. Therefore, in a preliminary step, selected the type of cable (that is its K) he is able to define in the commercial series the conductor section S complying with the expression

$$S \geq I_k \sqrt{t}/K \quad (18)$$

In reference to the previous sample case that consider a time t=1cycle, the conductor section of the EPR cable is obtained as the ratios I_k/1011(50Hz) and I_k/1107 (60Hz).

In a complementary way, when it is selected the actual protective device, the designer can verify the section value S calculated by the (18) adopting the expression

$$S \geq \sqrt{I_k^2 t} \Big/ K \quad (19)$$

In fact, for each short-circuit current value I_k, the manufacturers of the protection devices provide the value I_k^2t of specific let-through energy that the device lets through.

In conclusion, selected the section S value of the circuit conductors and knowing the let-through energy I_k^2t, it is possible to calculate for copper (Cu) cables as well as for aluminum Al cables, the effective final temperature of the short-circuit event also assuming as initial value the operating value $T_i = T_z$ or the effective initial value $T_i < T_z$ if known

- for copper (Cu) cables

$$T_f = ((T_i + 234.5) * 10^{I_k^2 t / 117612 \cdot S^2}) - 234.5 \quad (20)$$

- for aluminum (Al) cables

$$T_f = ((T_i + 228) * 10^{I_k^2 t / 49500 \cdot S^2}) - 228 \quad (21)$$

The knowledge of the actual final temperature T_f for each single short circuit event of t duration allows to determine the life loss rate calculating the effective coefficient RTC (4)

$$\log_{10}\left[RTC\left(T_f\right)\right]=\frac{b\cdot\left(T_f-T_i\right)}{\left(T_f+273\right)\cdot\left(T_i+273\right)} \qquad (4)$$

It is possible to evaluate that temperature values $T_f \cong T_k$ cause the RTC to take on values that are sensitive or high percentages compared to the same nominal life D_n expected for the cables. Assuming the tripping time t as lived at temperature T_f and expressed in h, the loss of life suffered by the cable in h is equal to:

$$LLR(t)=RTC(T_f)\times t \qquad (5)$$

To avoid faster degradation of the cable insulation, the tripping time has to remain very short. Therefore, considering that times of the order of one cycle weigh 5.6 10^{-6} h at 50Hz and 4.6 10^{-6} h at 60Hz, the LLR remains very limited.

In any case, known LLR, it is possible to update the overall value of the lived life LL of the circuit by (6).

IV. CONCLUSIONS

The design of an electrical system is permanent and consists of two fundamental processes, from its correct conception and installation, to its operational management and monitoring of the life of its components. In correlation with each overcurrent event, the increase in natural aging can be evaluated. A procedure based on the Arrhenius law of the thermal aging of insulating materials allows to introduce the relative time coefficient (RTC) which evaluates the aging rate variation and to promote a simplified method for an estimate of the loss of life and the residual useful life of insulated electrical cables. The use of the suggested tools supports system operators in monitoring the loss of life of the cables of the selected circuits in actual conditions, to optimize their operation and, possibly, to improve the efficiency of the distribution system. Therefore, knowledge of the actual gap in lifetime that usually characterizes the operation of insulated electrical cables can contribute to improve the design culture and criteria. This paper highlights how in the case of transient - adiabatic events such as short circuits, the behavior of the circuits can be characterized by the analysis of the parameter impulse of current tolerable for the conductors.

REFERENCES

[1]. G. Parise, L. Parise, J. R. Harvey and M. A. Anthony, "The In-Op Design of Electrical Distribution Systems Based on Microsystem Criteria," in IEEE Transactions on Industry Applications, vol. 54, no. 1, pp. 32-38, Jan.-Feb. 2018, doi: 10.1109/TIA.2017.2743073.

[2]. IEC 60216-1:2013 Electrical insulating materials - Thermal endurance properties - Part 1: Aging procedures and evaluation of test results

[3]. G. Parise and L. Martirano, "Circuits operation control and overloads protection: power cables equivalent ampacities," in IEEE Transactions on Industry Applications, vol. 36, no. 1, pp. 22-29, Jan.-Feb. 2000, doi: 10.1109/28.821791.

[4]. G. Parise, L. Martirano, L. Parise, L. Gugliermetti and F. Nardecchia, "A Life Loss Tool for an Optimal Management in the Operation of Insulated LV Power Cables," in IEEE Transactions on Industry Applications, vol. 55, no. 1, pp. 167-173, Jan.-Feb. 2019, doi: 10.1109/TIA.2018.2866982.

[5]. G. Montanari: The compensation effect in the thermal ageing study of the insulating materials L'Energia Elettrica AEI November 1990 Vol LXVII pp. 485-497 Milano (Italy).

[6]. Xiao-Kai Meng, Zhi-Qiang Wang, Guo-Feng Li, "Dynamic Analysis of Core Temperature of Low-Voltage Power Cable Based on Thermal Conductivity", Electrical and Computer Engineering Canadian Journal of, vol. 39, pp. 59-65, 2016, ISSN 0840-8688.

[7]. P.K. David Correlation of Arrhenius Parameters: The Electrotechnical Aging Compensation Effect IEEE Transactions on Electrical Insulation vol EI-22 n. 3 June 1987 pp. 229-236

[8]. NEMA WC 3-1992, Rubber-Insulated Wire & Cable for the Transmission-Distribution of Electrical Energy (ICEA S-19-81).

[9]. NEMA WC 5-1992 (Rev 1996), Thermoplastic-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy (ICEA S-61-402).

[10]. NEMA WC 8-1988, (Rev 3, 1996) Ethylene-Propylene-Rubber-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy (ICEA S-68-516)

[11]. "IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (IEEE Buff Book)," in IEEE Std 242-2001 (Revision of IEEE Std 242-1986) [IEEE Buff Book] , vol., no., pp.1-710, 17 Dec. 2001, doi: 10.1109/IEEE STD.2001.93369.

[12]. G. Parise, L. Martirano and L. Parise, "Life Monitoring Tool of Insulated Cables in Photovoltaic Installations," in IEEE Transactions on Industry Applications, vol. 50, no. 3, pp. 2156-2163, May-June 2014, doi: 10.1109/TIA.2013.2283197.

[13]. IEC Standard 60364, "Electrical installations of Buildings," Part 5: Selection and erection of electrical equipment - Wiring systems edition 3 – 2009.

[14]. IEC Standard 60364 "Electrical installations of Buildings," - Part 4-43: Protection for safety - Protection against overcurrent ed.2008

[15]. NFPA 70, National Electrical Code 2023 Edition

G. Parise, "Density of currents and of withstand electric charges admissible for the conductors," 2018 IEEE/IAS 54th I&CPS, Niagara Falls, ON, Canada, 2018, pp. 1-6, doi: 10.1109/ICPS.2018.8369990.

BIOGRAPHY

Giuseppe Parise (M'82-SM'03-Fellow'10-Life Fellow'15) received his M.S. degree in Electrical Engineering from Sapienza University, Rome Italy in 1972. From 1973 to 2017, he was with the Faculty of Engineering, Sapienza University of Rome, where he was a Full Professor of Electrical Power Systems and is adjunct professor. He has authored about 400 papers, two patents, and four papers that received Prize Paper Awards by IEEE/IAS PSD. He is General President of AEIT- Italian Association of Electrical, Electronics, Automation, Information and Communication Technology and President of Association of Safety Technology Research for Industry (ASTRI). Since 1983 he has designed power electrical systems in building complexes. From 1983 he has been and continues to serve as an expert member of Superior Council of Ministry of Public Works (Italy), as member of the Road Tunnel Standing Committee since 2017 and PIARC member of CT 4.4. He is active in the IEEE Industry Applications Society (past Member at Large of Executive Board), chair of the two subcommittee I&CPS Forensics and Ports, and Distinguished Lecturer 2019-2021. He is chair of the R8 Area Chapter and of the Italy Section Chapter IA34. He is IAS Associate Member of Governors Board of Society of Social Impact of Technology SSIT. He has been a Registered Professional Engineer in Italy since 1975. (parise@ieee.org)