Estimation of Cable Maximum Operating Temperature Based on ANN Approach

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Abstract

In this paper, an artificial neural network (ANN) based approach is used for estimation of cable maximum temperature under operational conditions. The most susceptible aspect of power cables is their thermal stability in operational conditions. Estimation of cable maximum temperature during the load cycling can assure the network operator from the cable safe operation. In this paper, some substantial factors which affect the cable thermal behavior are selected as the ANN inputs. A two-layer ANN is formed for cable maximum temperature estimation and is trained by experimental result of cable temperature variation data during different operational conditions. Finally, some other experimental results are applied for evaluation the ANN capability. Results show good accordance of ANN estimations with the real experimental measures.

1. Introduction

In the competitive and uncertain context of the deregulated electricity market, distribution utilities are pushed on one hand towards the improvement of power quality, and on the other hand towards the reduction of costs. In this respect, a decrease in the expenses associated with maintenance and replacement of failed components is particularly desirable, since it can be accomplished through a reduction in component failures, which also has a positive effect on power quality, too [1].

In the case of HVAC cables, failure rate reduction is made possible in principle by the fact that they are usually designed neglecting load cycles, and assuming conservatively the temperature at the conductor-insulation interface to be constant and equal to its rated (design) value, i.e. the maximum permissible temperature for continuous operation of the chosen insulation. Hence, life estimation of HV power cables at the design stage is commonly performed irrespectively of load cycles, since at that stage the actual time variation of loads is not known in detail [2].

On the contrary, the actual load current varies with time following more or less periodical cycles. This variation is under the constraint that the rated current is not to be exceeded unless by a limited amount and for short periods. Actually, load currents vary with time according to daily cycles. This current is well below the rated current for most of the duration of the cycles, with the exception of short periods and by limited amounts.

This problem will be highlighted further when the understudied component is underground cable. Because of the weak heat transfer of the underground cables, their operational temperatures are directly impressed by the load cycles. On the other hand, the procedure of estimation of the cable thermal transients needs several inputs which depends on the configuration of cables inside the ground, kind of soil and many other factors [3].

However, in some cases the network operator does not need to know the accurate cable thermal variation trajectory, but he needs to know if the cable reaches to its maximum allowed temperature or not. It is required the operator to be enabled to estimate the maximum cable temperature under definite operational conditions. Hence, in this paper an ANN based approach is utilized for estimating the maximum temperature of power cables during different operational conditions which can inform the utility staff about the safe operational conditions of the network cables.

2. Problem Statement

Major stresses that wear out the cable insulation are: electrical stress caused by voltage; thermal stress caused by Ohmic losses in the conducting parts, dielectric losses in the insulation and – in some cases – environmental heating from the ambient [3].

For polymeric insulation of HVAC cables, a model holds within typical test and service ranges of electrical and thermal stress. This model is the combination of two popular single-stress models (i.e., the Arrhenius model for thermal life and the inverse power model (IPM) for electrical life) and can be written as [4]:

$$L = L_0 \left(\frac{E}{E_0} \right)^{-(n_0 - bcT)} \exp(-BcT) \quad (1)$$

Where E is the maximum electric field, $cT = 1/T_0 - 1/T$ is the so-called conventional thermal stress (T is the maximum temperature in Kelvin degrees, and T_0 is a proper reference temperature, commonly that of the ambient), n_0 is the so-called voltage endurance coefficient (VEC) at $T = T_0$, E_0 is a value of the electric field below which electrical aging is deemed as negligible, L is time-to-failure (life), L_0 is life at $T= T_0$ and $E = E_0$, B is equal to W/k (W is the activation energy of the main thermal degradation reaction and k is the Boltzmann's constant) and b is a parameter that rules the synergism between electrical and thermal stress.

The maximum stresses applied to an HVAC power cable are maximum temperature and electric field in the insulation. Whereas the maximum electric field can be hypothesized as constant with time and equal to its design value (En) – applied voltage being more or less steady – maximum temperature varies during the load cycle. This is due to variation of power losses with respect to the variation of the load as well as to heat storage and exchange properties of the layers that constitute the cable and its outer environment [5]. The combination of these effects gives rise to a thermal transient during which temperature starts from an initial value and tends towards a steady value. For example, if a 145 kV XLPE-insulated power cable having 630 mm^2 copper conductor is subjected all over its service life to the daily load cycle sketched in Fig. 1, its temperature transients within each ith current step (i = 1, …, 6) are reported in Fig. 2 (solid lines), together with the relevant steady state temperature (dashed lines) [1].

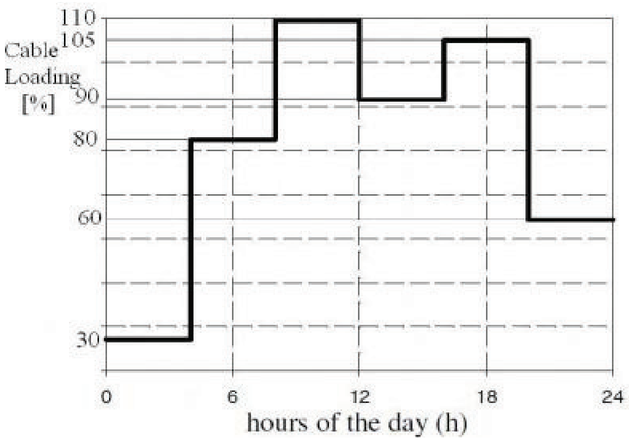

Fig. 1. Stepwise-constant daily load cycle (6 equally lasting current steps) [1]

According to Fig. 2, when the cable overloads within steps 3 and 5, the steady state temperature violates the maximum withstand temperature of insulation (90°C).

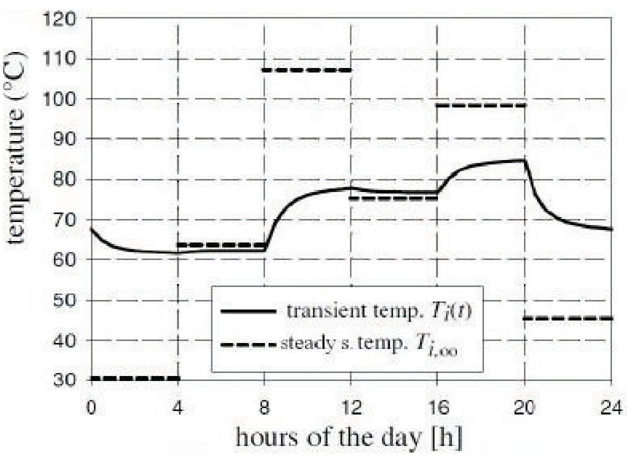

Fig. 2. Transient temperature (solid line) and steady state temperature (dashed line) within step of load cycle if Fig. 1 [1]

Also, in the light load periods (steps 1 and 6), the steady state temperature is well below the maximum temperature. However, the steady state temperature is the temperature that the cable reaches while the cable load is equal to its corresponding step of the load cycle for a long time. But usually in the daily load cycle, the load does not remain constant and changes periodically (e.g. Fig. 1). Therefore, as can be seen in Fig. 2, cable transient temperature is much different from the steady state temperature and in this example, the cable temperature always remains below the rated value (90°C).

The transient temperature within the load variation is determined via an ad hoc transient thermal model [4], under the assumption of a stepwise-constant daily load cycle. The variation of the cable conductor temperature during a stepwise-constant load cycle can be determined by calculating the thermal response of the HVAC cable and surrounding environment to each step change of the load current. Such a response as discussed in the literature, can be attained by representing the layers that constitute the cable and the environment as a lumped-parameter ladder network of series thermal resistances (that account for the heat-exchange properties) and shunt thermal capacitances (that account for heat storage properties), and applying to this network the thermal analog of transient Ohm's law (see [4]).

Calculating the thermal transient of power cables using the mentioned thermal network analog needs complete information about the cable installation conditions and an expert who is familiar with the related equations and calculations. However, in some cases the network operator does not need to know the accurate cable thermal variation trajectory, but he needs to know if the cable reaches to its maximum allowed temperature or not. It is required the operator to be enabled to estimate the maximum cable temperature under definite operational conditions.

Therefore, a practical requirement raises here and that is the need for a simple and practical estimation method for estimating the cable maximum temperature in the networks with many different laying structures and considering the load variations of the cables. Here in this paper, in order to simplify the process of cable temperature behavior estimation, a method based on the ANN approach is proposed. This approach tries to model the cable maximum temperature considering its load cycles. The results are compared to the experimental values and the accuracy of the approach is shown.

3. Estimation of Maximum Cable Temperature

Since the heat generation rate inside the power cable changes proportional to magnitude of cable through current, the temperature variation of the cable tracks its load current fluctuations. However, the temperature tracks the load variations with thermal inertia proportional to the cable thermal constant.

Therefore, the prediction of cable thermal transient behavior becomes complicated and needs huge equations as mentioned in literature. In order to overcome the complexity, the estimation of cable maximum temperature would be helpful.

In the first stage, the artificial learning characteristic of ANN is exploited to learn the estimation of the cable maximum temperature according to data extracted from the load cycles. Then, by using the generalization characteristic of the ANN, the maximum temperature of other cables during different load cycles is estimated. The maximum cable temperature is the only output of the neural network.

The important point in designing the structure of artificial neural network is suitable selection of neural network inputs. The inputs should be defined in a manner that all the parameters affecting the cable temperature are taken into account. Four parameters which are considered for ANN inputs are as follows:

a) Normalized value of maximum load
b) Load factor
c) Electrical resistance of conductor
d) Normalized value of ground temperature

The magnitude of the maximum load directly affects the rate of temperature rise in the peak load interval. Since the designed ANN is going to estimate the maximum temperature for different cables with different cross sections, the maximum load of the cable is normalized based on the maximum permissible load of the cable.

Obviously, the maximum cable load cannot introduce the nature of load by itself. Another parameter is also needed to present the mode of daily load variations. Load factor *LF* is the ratio of *Pav* to *Pmax*. *Pmax* and *Pav* are the maximum and average load magnitudes, respectively. The concept of the average load of a typical daily load cycle is also demonstrated in Fig. 3.

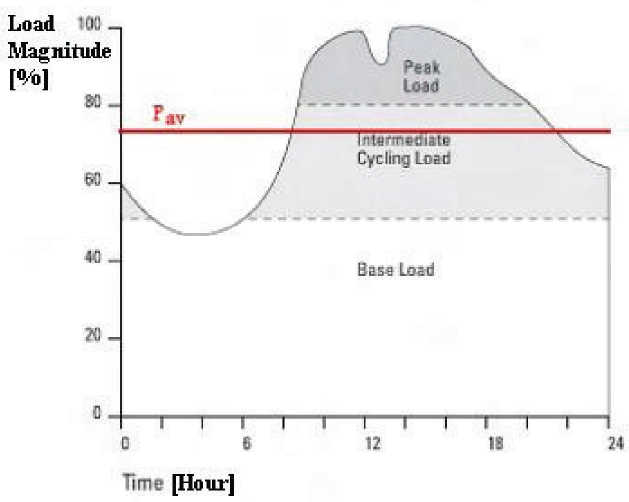

Fig. 3. Cable typical daily load cycle

The Type of conductor and its cross section have a direct relationship with temperature rise of the cable. These two factors can be indicated by electrical resistance of the cable per unit length.

Finally, the environment (ground) temperature which the cable is installed inside, affects the maximum cable temperature; because the no load temperature of the cable is approximately equal to ambient temperature and any cable load increment leads to cable temperature increase which is added to ambient temperature. Since other ANN inputs are in the range of one, the ambient temperature is initially normalized on the basis of 20°C and then is given to ANN. The temperature of 20°C is the temperature which is often used in nominal specification calculations for power cables.

All aforementioned inputs and one output (cable maximum temperature) are considered for designing the artificial neural network. After experimentation, an ANN model with one hidden layer and four hidden neurons in the hidden layer yields the best results. A diagram of the ANN model for maximum cable temperature prediction is shown in Fig. 4.

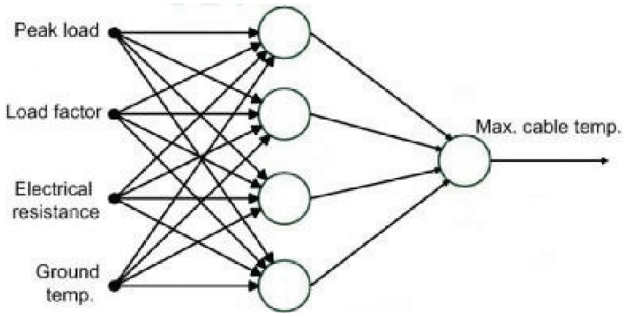

Fig. 4. ANN model for maximum cable temperature estimation

This model has an MLP (Multi-Layer Perceptron) structure and the activation functions of the hidden neurons are mono-polar sigmoid function. The output neuron has linear summation as activation function. The model uses the data to learn the relationships between inputs and the output. The gradient descent backpropagation algorithm with adaptive learning rate is used for training the ANN because it has the ability to generalize beyond the training data.

It is worthy to note that characteristics and the geometry of the various cable layers are not considered as the ANN inputs. The reason is the existence of cable ampacity in the nature of one of the ANN inputs, namely normalized value of the maximum cable load. As mentioned before, this input is the ratio of cable maximum load to its ampacity. Since the heat transfer of cable dielectric and its characteristics and the geometry are considered in the cable ampacity calculations, the specification of cable dielectric is not considered as a separate input of the ANN.

4. Results

The data which are used for training the ANN are presented in Table 1. As mentioned before, these data have been collected from the literature [4, 6, and 7]. In fact, the data related to the last row of Table 1 present the desired output of the ANN. After training the neural network using data from Table 1, it is now time for ANN performance evaluation. For this purpose, another data set just like Table 1 is required. Thus, data of Table 2 are provided [1, 3, and 7].By applying the data of Table 2 to the ANN, the estimated values of the maximum cable temperatures provided by ANN are presented in Table 3. The desired values of maximum cable temperatures are also reported in this table [1, 3, and 7].

As observed in Table 3, the results have some errors. The main origin of the errors is lack of experimental data regarding the thermal behavior of power cables in different load cycles. These data are required for better training of the ANN. However, despite the trivial data available, the estimation has been done for different cables of different voltage levels. This indicates that this approach has prevented the specialized calculations which were necessary for different maximum cable temperature estimation.

Table 1. Specification of the cables which were used for training the ANN

Cable No.	1	2	3	4	5	6	7	8	9	10
Cable Ampacity [A]	400	350	840	350	1015	400	350	400	350	945
Peak Load [A]	530	480	840	500	1088	550	480	475	450	1088
Load Factor	0.63	0.63	0.7	0.35	0.71	0.5	0.5	0.75	0.75	0.71
Electrical Resistance [Ω/km]	0.05	0.058	0.038	0.058	0.031	0.05	0.058	0.05	0.058	0.031
Conductor Type	Al*	Al	Cu	Al	Cu	Al	Al	Al	Al	Cu
Cross Section [mm^2]	785	590	630	590	800	785	590	785	590	800
Ambient Temp. [°C]	25.9	25.9	20	23.5	20	30.3	30.3	16	20.2	20
Insulation Type	XLPE	XLPE	EPR	XLPE	XLPE	XLPE	XLPE	XLPE	XLPE	EPR
Nominal Voltage [kV]	15	15	145	15	145	15	15	15	15	145
Max. Temp. during Loading [°C]	88	86.5	80	82	78	87.9	86.5	74.5	86.5	92

* Aluminum

Table 2. Specification of the cables which were used for performance evaluation of the ANN

Cable No.	1	2	3
Cable Ampacity [A]	905	1015	400
Peak Load [A]	995	1088	350
Load Factor	0.72	0.75	1
Electrical Resistance [Ω/km]	0.038	0.031	0.05
Conductor Type	Cop	Cop	Al
Cross Section [mm^2]	630	800	785
Ambient Temp. [°C]	20	20	24.4
Insulation Type	XLPE	XLPE	XLPE
Nominal Voltage [kV]	145	145	15

Table 3. Estimated and real values of maximum cables temperatures

Cable No.		1	2	3
Maximum Temp. [°C]	Estimated Value by ANN	86.7	78.8	67.6
	Real Value	85*	83*	62.3
Error [%]		+2.0	-5.1	+8.5

5. Conclusions

This paper has presented a practical approach for estimating the maximum temperature of power cables considering their load cycling. Environmental conditions in considered as the environment (ground) temperature. The Trained ANN can estimate the maximum temperatures of different cables in different operational conditions in a good accordance with the experimental values. The provided ANN tool can simply help the utility staff in recognizing the operational conditions of their related network cables.

6. References

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