Life Expectancy Calculation for Electric Vehicle Traction Motors Regarding Dynamic Temperature and Driving Cycles

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Abstract—**Design optimization and power density of electric motors are in many cases determined by motor temperatures and life expectancies of the motor insulation. Especially for electric vehicle traction motors, the motor temperature is variable and dependent on the actual usage of the vehicle. This paper presents a method that allows for a calculation of motor life expectancies with regard to variable periodic motor temperatures. The temperatures are derived from assumed periodic driving cycles and calculated with the powertrain simulation tool ADVISOR. Other sources, as for instance statistical data or actual measurements, can also serve as input source. The impact of short-term excess temperatures on the motor life expectancy can be considered and motor design optimizations may be disclosed.**

Index Terms—**Life expectancy, traction motor, electric vehicle, electrical motor, driving cycle**

I. INTRODUCTION

Today's automobile industry shows an upward trend towards the design and production of vehicles with electric-powered drives (EV). As long as small series and test vehicles dominate, the economic pressure to design highly optimized and cost effective electric drives is less distinct. However, when it comes to mass production, a material saving and simple motor and cooling design of the electric drive may result in significant reduction of cost, weight and complexity of the product. In order to meet lifetime requirements and to disclose further cost and weight reducing design measurements, a life expectancy estimation of the considered motor has to be performed. Lifetimes or service times of current conventional vehicles are denoted in kilometers or miles due to mechanical wear and fatigue that is the main aging factor [1]. For instance, intended lifetime characteristics for designing a conventional medium-sized car may be around 160,000km in terms of drive distance or 6,000h to 8,000h in terms of vehicle run time. Therefore, designing a motor that lasts significantly longer than other crucial parts of the vehicle may result in unnecessary extra costs of resource and energy consumption.

In contrast to conventional motors, electrical motors comprehend additional aging characteristics or aging design aspects. Motor aging factors can be grouped into four classes that describe mechanical, electrical, environmental and thermal aspects. For instance, mechanical wear and fatigue of the bearings are the main cause of failures of mains-operated standard motors [2]. Depending on the applied load, mechanical stresses also cause broken rotor bars in induction machines [3]. Modern frequency converter driven motors face additional electrical aging effects such as bearing currents and high electrical stresses on the motor insulation due to voltage peaks at the motor terminal or within the motor coils [4]. Humidity, greases or salts in the motor or external vibration are environmental effects that lead to degradation and aging of the insulation system. For this reason, many traction motors for cars are constructed using resin casting technologies that help to protect rotor and stator winding from environmental factors and provide more mechanical stability.

This paper focusses on thermal aging of the insulation system on the basis of assumed driving and temperature cycles. The available space for electric drives in cars is frequently very limited. Therefore, a compact motor design with a high power density is a design objective. Then, thermal aging of insulation components becomes a crucial characteristic [5]. Since thermal aging is caused by molecular deterioration, it takes effect on the basis of temperature, regardless of whether the vehicle is in movement or standstill [6]. Therefore, a life expectancy calculation of electric vehicle motors ought to bring into focus the actual temperature and usage cycles the motor is exposed to. A simple assumption of constant motor temperature does not sufficiently model aging effects of short-term excess temperatures, temporal activation of the cooling system etc, as it is proposed by [7].

II. CONSTANT DUTY OPERATION

Motor faults and aging effects of low-voltage motors can have very different causes [2]. The thermal aging effect on the insulation is a crucial lifetime parameter. Its aging rate is equivalent to the chemical deterioration law of Arrhenius [6] and can be expressed by

$$L = B \cdot e^{\frac{\varphi}{kT}} \tag{1}$$

whereas B is a constant, φ the chemical activation energy in eV, T the absolute Temperature in K and k the Boltzmann constant. For calculation, a derived formulation of (1) is recommended

$$L(\vartheta_c) = L_0 \cdot 2^{\frac{\mathrm{TI}-\vartheta_c}{\mathrm{HIC}}} \tag{2}$$

whereas ϑ_c is the constant duty hot spot temperature of the machine winding in °C, TI the temperature index (reference temperature) in °C, L_0 the reference lifetime in h that is generally set to $L_0 = 20,000$h and HIC the halving index in °C that corresponds to the 8° to 10°C Montsinger rule [8], [9], [10], [11]. TI and HIC are specific properties of the insulation system and can only be determined accurately by empiric long-term aging and overload tests, as for instance

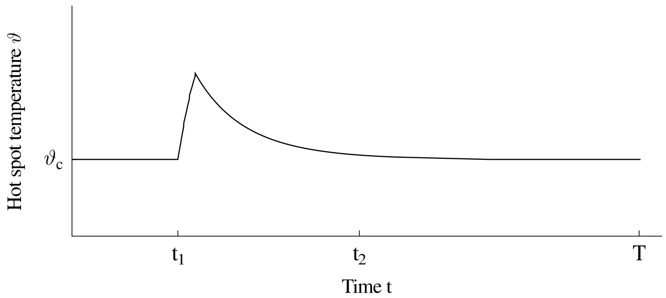

Figure 1. Short-term excess temperature interval (t_1, t_2) within period T.

recommended in [12]. The hot spot temperature is assumed to be the critical temperature that determines the failure of the considered insulation system. The hot spot temperature can only be measured indirectly and must then be estimated [13]. (2) is only valid for constant duty operation, i.e., constant temperature.

According to (2), lifetime L constitutes a single time value denoted in h. Information concerning a failure distribution that are necessary in order to use reliability theory and to calculate reliability functions cannot be derived by this way [14]. (2) does not make any statement about the actual distribution of insulation system failures due to thermal aging. However, it is likely to find failures around the calculated lifetime L, as could be observed by [9].

III. Dynamic Operation

Thermal damage to drives and transformers are also caused by short-term overload and excess temperatures. A corresponding lifetime loss can be calculated according to [15]. This approach assumes the chemical deterioration damage due to temperature to be time-independent and additive. An percentage aging or residual lifetime factor is defined as

$$p(t_1, t_2) = \int_{t_1}^{t_2} \frac{1}{L(\vartheta)} \mathrm{d}t = \frac{1}{L_0} \int_{t_1}^{t_2} 2^{\frac{\vartheta(t) - \mathrm{TI}}{\mathrm{HIC}}} \mathrm{d}t. \quad (3)$$

Then, the lifetime loss of the excess temperature time interval (t_1, t_2) can be calculated by

$$l_{1,2} = p(t_1, t_2) \cdot L(\vartheta_c). \quad (4)$$

The lifetime loss $l_{1,2}$ is the aging time in h in contrast to the actually passed time of time interval (t_1, t_2). It gives an illustrative statement on how much extraordinary short-term thermal stresses decrease insulation lifetime and can be used to calculate residual (remaining) lifetimes of motor insulations [5]. However, in order to use lifetime as a design parameter for varying motor temperatures, a different approach seems to serve more appropriately. For this purpose, a usage or service lifetime L_p shall be considered here, based on an assumed periodic duty and temperature cycle. Period T comprehends an excess temperature time interval besides constant duty operation as illustrated in Fig. 1. All time periods of excess temperature $n(t_2 - t_1)$ are substituted by the corresponding time of life loss $n \cdot l_{1,2}$ to

$$L_p = L(\vartheta_c) + n(t_2 - t_1) - n \cdot l_{1,2} \quad \text{with} \quad n \approx \frac{L_p}{T}. \quad (5)$$

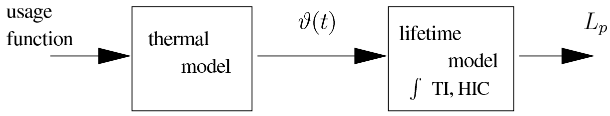

Figure 2. Life expectancy calculation chain.

n is the number of periods T within service lifetime L_p. If the time interval of excess temperature (t_1, t_2) is extended to period T and (5) is rearranged, the service lifetime can be calculated as

$$L_p = \frac{T}{p_T}. \quad (6)$$

(6) permits a life expectancy calculation not only on the basis of simple exponential temperature functions as shown in Fig. 1, but allows for a consideration of arbitrarily varying motor temperatures within a period T. According to (3), varying temperature values can be numerically integrated on the basis of actual temperature data or simulation results. Contrarily, common standard lifetimes denoted in time describe an invariable steady use [1]. Besides the driving cycle period, lifetime L_p comprehends additionally all time periods when the car is actually not in use. L_p is determined by the insulation parameters, the drive specific components such as cooling system, losses and thermal behavior and the actual usage function, Fig. 2.

IV. EV Motor Temperatures and Driving Cycles

In the following a simulation of driving characteristics of an EV with 30kW induction motor based on an assumed driving cycle is to be considered. The simulation has been performed with the power-train simulation tool ADVISOR 2.3 [16]. Lifetime parameters have been calculated using the software tool MATLAB. The assumed driving cycle is a combination of three standardized EPA Highway driving cycles as can be seen in Fig. 3. Of course, any other driving cycle, combination of driving cycles or statistical user data or measurements can serve as input requirement. An active cooling system is neglected. The thermal motor model in ADVISOR 2.3 is simple and based on a single heat capacity. More complex models, as for instance proposed by [17], may deliver more reliable results since they provide calculations of inner winding and hot spot temperatures. The insulation properties are assumed to be found to HIC = 10°C and TI = 145°C.

In Fig 3 and Fig. 4 the results of the performed simulation are depicted. They show the entire driving period to last 43min and the temperature period that comprehends a subsequent cooling phase to last ca. 3.5h. First, the simulated temperature rises due to motor losses up to the point when the last driving cycle ends. Then, in standstill, the motor emits its heat to the ambience and the simulated temperature decreases exponentially according to the underlying thermal model.

In the following, a daily repetitive usage of the EV is assumed by setting the period to $T = 24$h. Hence, the idealized

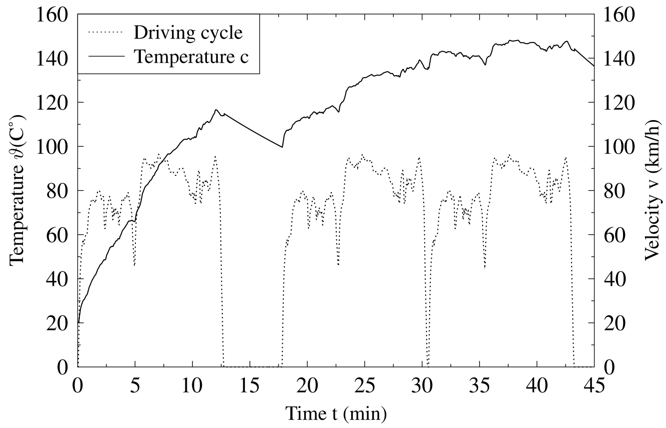

Figure 3. Simulation of driving cycle.

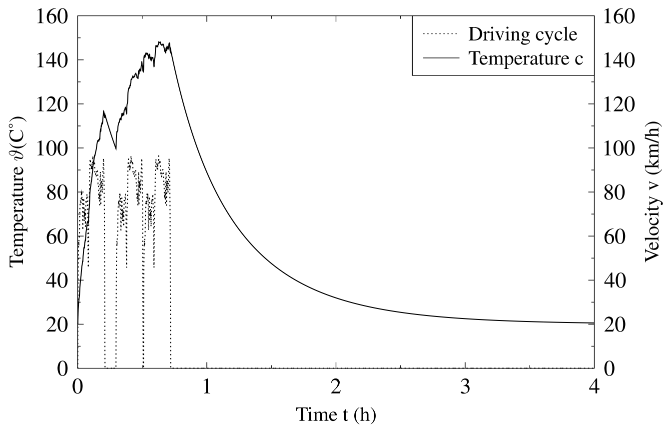

Figure 4. Simulation with cooling phase.

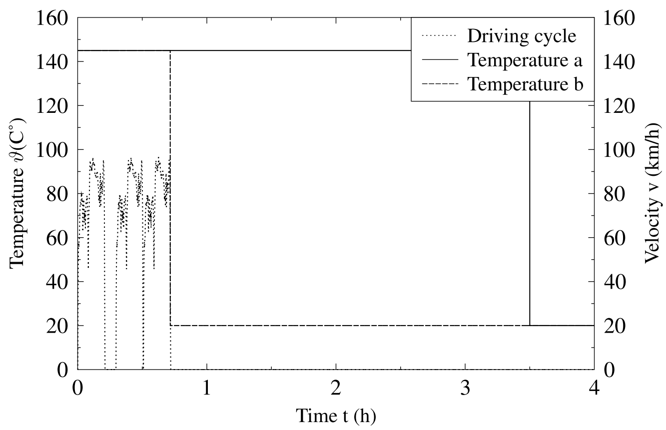

Figure 5. Assumed temperature characteristic.

		a (3.5h)	b (43min)	c (simulation)
ϑ	(C)	145°/20°	145°/20°	variable
p_T	(‰)	0.1752	0.0360	0.000665
L_p	(a)	15.64	76,05	4,120
d_L	(km)	282,576	1,374,033	74,438,100
T_L	(h)	4,091	19,893	1,077,723

Table I
CALCULATED AND SIMULATED LIFETIME PARAMETERS.

		a (3.5h)	b (43min)	c (simulation)
ϑ	(C)	145°/0°	145°/0°	variable
p_T	(‰)	0.1750	0.0358	0.000574
L_p	(a)	15.65	76.365	4,770
d_L	(km)	282,756	1,379,562	86,181,975
T_L	(h)	4,081	19,880	1,247,753

Table II
LIFETIME PARAMETERS WITH AMBIENT TEMPERATURE OF $\vartheta = 0°$C.

driver uses his car every day in the exact same manner and covers a distance of 49.5km in 43min. The excess temperature interval (t_1, t_2) lasts 3.5h whereas in the residual time of 20.5h the motor temperature equals the ambient temperature, that is set to $\vartheta_c = 20$°C. Three cases of life expectancy calculations are compared in Tab. I. The corresponding percentage aging factors p_T and service lifetimes L_p are calculated. Additionally, lifetime design parameters are calculated that are the driven distance d_L and the vehicle run time T_L with respect to the motor insulation.

In Fig. 5 two rough temperature estimations, (a) and (b), that simplify the actual temperature characteristics in the motor by rectangular blocks are depicted. These simple assumptions may be used for conservative life expectancies estimations. The slow heating-up of the EV motor that can be seen in the simulation results depicted in Fig. 3 and the exponential cooling phase are calculated with a maximum allowed temperature of $\vartheta = 145$°C that is chosen by the motor designer as worst case. In (a) the total temperature cycle that lasts ca 3.5h is estimated by a block characteristic whereas in (b) only the driving cycle phase, i.e., the actual vehicle run time of 43min, is estimated by a temperature block and the subsequent cooling phase is neglected, Fig. 5. (c) is the actual simulation that respects the varying temperature behavior.

Tab. I shows the calculated lifetime parameters that can be compared with desired target lifetime parameters, as for instance $T_L = 7,000$h and $d_L = 160,000$km. The rough temperature estimation of (a) is closest to these values. In fact, the run time T_L of estimation (a) is less than the target value. This can be traced back to high velocities of the chosen highway driving cycles and may give different results on the basis of urban driving cycles. Estimation (b) considers only driving time to be relevant and leads to significant higher lifetime values. The temperature characteristic of simulation (c) may give a more realistic picture of motor heating. The lifetime parameters of (c) in Tab. I are greater by several orders of magnitude compared to the estimations of (a) and (b). The great difference between these values is due to the exponential character of (2). In the case of the simulation requirements, a motor designed on the basis off these simplifying estimations is probably oversized.

Critical life lost is generated in the period of peak temperature in Fig. 4. Due to Montsinger's rule, all points in time when the motor temperature equals ambient temperature or is significantly less than peak temperature do not contribute considerably to the thermal aging process. Tab. II presents the same calculations based on an ambient temperature of $\vartheta = 0°\text{C}$ in the residual time of 20.5h. As can bee seen, the differences in estimation (a) and (b) to the previous calculations are negligible. The difference in simulation (c) is greater since the maximum peak temperature is hold for a short period in time. Insulation lifetime is not determined by the level of ambient temperature.

V. CONCLUSIONS

Simple assumptions of constant duty temperatures of EV motors are insufficient when significant temperature cycles are to be expected and they may lead to estimation errors and improper motor designs. Instead of designing motors with respect to a fixed allowed temperature, a consideration of actual usage data may disclose motor design optimizations. Thinking about life expectancy, engineers frequently focus on technical issues of their drive systems such as insulation classes etc. However, life expectancy due to temperature aging principally depends at least as much on usage or usage functions as it depends on machine properties. Therefore, in order to develop an adequate and not oversized drive system, precise and reliable specifications of usage have to be available, for instance, derived from customer data.

The critical aspect concerning thermal life loss and life expectancies are the number of peak excess temperatures within the usage. Therefore, a lifetime management for a traction motor of an electric vehicle ought to bring into focus the number, length an hight of peak excess temperatures. This aspect is dircely connected to the short-term overloads demanded by vehicle control and driver. Depending on the life state, an intelligent motor life management limits overloads in order to avoid further insulation deterioration. For calculating residual life expectancies whilst the drive system is in service, a prediction of future usage is essential. For this purpose, recorded log data can help to derive reasonable predictions.

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