Reliability-Oriented Design of Inverter-Fed Low-Voltage Electrical Machines: Potential Solutions

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Abstract: Transportation electrification has kept pushing low-voltage inverter-fed electrical machines to reach a higher power density while guaranteeing appropriate reliability levels. Methods commonly adopted to boost power density (i.e., higher current density, faster switching frequency for high speed, and higher DC link voltage) will unavoidably increase the stress to the insulation system which leads to a decrease in reliability. Thus, a trade-off is required between power density and reliability during the machine design. Currently, it is a challenging task to evaluate reliability during the design stage and the over-engineering approach is applied. To solve this problem, physics of failure (POF) is introduced and its feasibility for electrical machine (EM) design is discussed through reviewing past work on insulation investigation. Then the special focus is given to partial discharge (PD) whose occurrence means the end-of-life of low-voltage EMs. The PD-free design methodology based on understanding the physics of PD is presented to substitute the over-engineering approach. Finally, a comprehensive reliability-oriented design (ROD) approach adopting POF and PD-free design strategy is given as a potential solution for reliable and high-performance inverter-fed low-voltage EM design.

Keywords: physics-of-failure; reliability-oriented design; partial discharge; thermal degradation; inverter-fed machine

1. Introduction

Transportation electrification represents the main promotion of reducing greenhouse gas emissions and fuel consumption [1,2]. The electrical drive is seen as the very center of this effort and the electrical machine (EM) is commonly treated as the primary contributor to weight and loss [3]. Thus, EMs with high power density are required for aerospace and automotive applications [4,5]. The two common ways to improve the power density are increasing the current density and/or using higher switching frequencies for higher speed [6]. However, both methods will add stress to the insulation system which leads to a reduction in reliability. Moreover, there is a trend of adopting higher DC link voltage. With the same power rating, higher DC link voltage will reduce the current, and consequently, the Joule losses will decrease (higher efficiency and simpler thermal management) as well as the cabling weight/size. Nonetheless, the higher DC link voltage increases the risk of PD inception which also challenges the reliability. Thus, trade-off between performance and reliability is demanded for inverter-fed low-voltage EMs. Currently, EMs are being developed following the so-called performance-oriented design as shown in Figure 1a [7]. Advanced approaches like thermal management are adopted to improve the performance and reduce the size [8,9]. However, reliability is not considered as a design objective during the development stage, but it is guaranteed by the over-engineering approach (e.g., increase

the insulation grade, use double insulation, etc.,). The EM's over-engineering is in contrast with the requirements demanded in modern applications, since the insulation thickness can have a great impact on size, power density [10,11], and heat dissipation of EMs which prevents EMs from reaching higher performance [12].
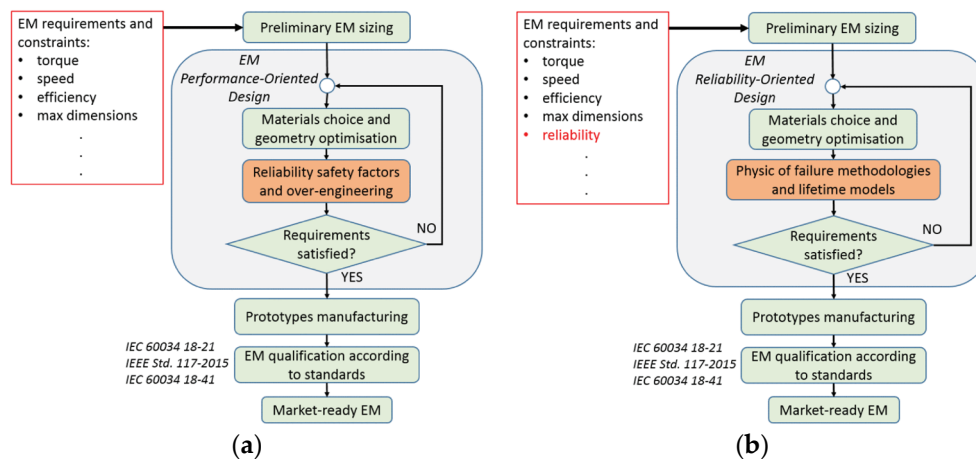

Figure 1. Flowchart of the two machine design strategies: (**a**) performance-oriented design; (**b**) reliability-oriented design.

POF approach is a possible solution to meet modern applications specifications. This method takes operational and environment conditions into consideration and predicts the lifetime of each component based on a set of equations which can be termed as the lifetime model. These models are usually derived from understanding the physics of degradation mechanism or they are based on database built through gained experience. POF has been used for power electronics [13] which represent the bottleneck in terms of reliability (i.e., less reliable component) in an electric drive. By pushing EM's limits to achieve higher efficiency, better performance, and lower weight, the EM reliability level decreases [14]. Hence, more focus should be given to the EM reliability compared to what was done in the past where: (1) EM designers gave low priority to the EM reliability and/or (2) the EM was just over-engineered. Therefore, the POF approach could be applied also in the study of the EM failure mechanism to achieve an EM reliability level able to comply with both (1) the reliability figures needed in safety-critical applications and (2) the upcoming technology (e.g., high-frequency switching device). Recently, there is a trend toward adopting POF at the EM design stage, i.e., reliability-oriented design (ROD), as shown in Figure 1b and discussed in [7]. According to the past surveys on EMs, bearing and winding insulation are mainly responsible for EM failure [15–18]. However, the fast-switching rate of the wide-bandgap (WBG) semiconductors such as SiC and GaN (high dv/dt), and the increase of DC-link voltage tend to make insulation failure prevalent compared to mechanical failures. Moreover, there are reliable lifetime models for bearing supplied by the manufacture (e.g., SKF). Additionally assuming appropriate scheduled maintenance and replacement procedures [19], i.e., if the bearings are adequately lubricated, then the bottleneck of EM's reliability becomes the winding insulation system [20,21]. Thus, this paper will take the winding insulation as a key driver for EM's reliability and focus on its failure modes will be given.

According to IEC standards [22,23], EMs with rated voltage below 700 V commonly adopt the Type I insulation which is made with organic materials, while EMs with rated voltage above 700 V typically employ the Type II insulation which is made with mixed organic/inorganic materials. The failure mechanism is quite different between the two insulations system. The occurrence of PD means the end-of-life for Type I insulation while EMs with Type II insulation can withstand PD to some extent. The research target of the paper will be limited to low-voltage machines adopting a Type I insulation system, which is commonly used in transportation electrification applications [24,25]. In addition, the

development of the switching technology offers the merits of switching loss minimization and more stable torque [26], but increases electrical stress to the insulation system especially when modern technologies are involved (i.e., SiC and GaN). As a result, the failure mechanism of inverter-fed EMs is quite different from the mains-fed EM. The paper focuses on inverter-fed EMs which are dominant in nowadays electric drives.

This paper reviews past work which investigates insulation degradation mechanism and its implementation on the EM design. The main aim of the work is to bridge the gap between knowledge build-up in the dielectric area and the EM design and pave the way toward the ROD of EMs. The paper is organized as follows: a general overview of EM insulation stress and appropriate lifetime model selection is presented in Section 2, aiming to discuss the feasibility of adopting POF for inverter-fed low-voltage EMs. Section 3 focuses on avoiding the occurrence of PD which is commonly achieved by the over-engineering approach. A PD-free design methodology would be introduced through understanding the physics of PD. Finally, a comprehensive ROD process is presented as a potential solution to achieve a reliable and high-performance EM.

2. Enabling the POF Approach for Inverter-Fed Low-Voltage EMs

The main challenge for adopting the POF approach for EMs is to identify the insulation stress and find a proper lifetime model. This section starts with an introduction to the insulation stresses faced by inverter-fed low-voltage EMs and the concept of dominated stress (i.e., prevailing aging factor) is highlighted in order to select the suitable lifetime model. Finally, a possible and reasonable way of adopting the POF approach for inverter-fed low-voltage EMs is presented.

2.1. Insulation Stresses Acting on Inverter-Fed Low-Voltage EMs

In general, the winding insulation is subjected to the so-called TEAM stresses [27] which are thermal, electrical, ambient, and mechanical stresses. Each stress is introduced in detail in the following subsections.

2.1.1. Thermal Stress

Thermal aging is probably the most recognized reason which causes insulation degradation and leads to premature failure. The deterioration is basically an oxidation process. Indeed, at adequately high temperature, the chemical bonds within the insulation organic material tend to break, and oxygen is likely to attach the broken bonds. Therefore, the polymer chain becomes shorter and weaker which eventually leads to insulation breakdown [28]. Thermal degradation is a long-term process, whose influence on the insulation's probability of failure might start to be perceivable only after several hours of operation. Accordingly, accelerated aging tests are generally employed to study this phenomenon, and eventually to qualify the insulation. The test sample for an aging test could be either the whole EM or an equivalent small test model. The model containing all of the insulation elements proportionately reduced in size was developed by Cypher and Harrington [29] and is termed as "motorette". The two common structures of motorette are shown in Figure 2: "Configuration A", which is proposed in IEEE and IEC standards, is a general option for a wide range of EMs, while "Configuration B" is a more specific solution closely depending on the machine geometry. Both configurations are viable options, since the compulsory insulation system is considered. After the test sample preparation, the accelerated aging test is conducted following the procedure recommended in technical standard from IEEE [30] or IEC [31]. An example of test process for Class A insulation is shown in Figure 3. The thermal stress is considered as dominant/prevailing aging factor over mechanical and environmental stresses, although vibrations and humidity exposures are also performed. At least three test groups with different aging temperatures are needed for lifetime model derivation. A voltage test is used to check if insulation reaches the end-of-life for each cycle. After the voltage test, a series of diagnostic tests such as insulation resistance, loss tangent can be performed. Monitoring and recording the changes of these quantities may

help in better understanding the aging process. The investigation on properties change during thermal aging process can be focused on resistance [32–34], capacitance [33,35–38], dissipation factor [34,36,37], and PDIV [34,35], and application of these findings can be found in papers on condition monitoring of insulation degradation [39–44]. Moreover, the diagnostic test may be used to determine the end of test life, either complementing the voltage tests or replacing them [31]. As mentioned above, for low-voltage EMs adopting a Type I insulation system, the occurrence of PD generally means the end of sample life. Thus, the inception of PD can also be used as the end-of-life criterion [45]. After the test, life data can be post-processed through a statistical approach and fit into the well-known Dakin's equation for evaluating the reliability of the insulation system. Details are discussed in the following section. Considerations on how to conduct the thermal-accelerated aging test and relative data post-processing can be found in [46].
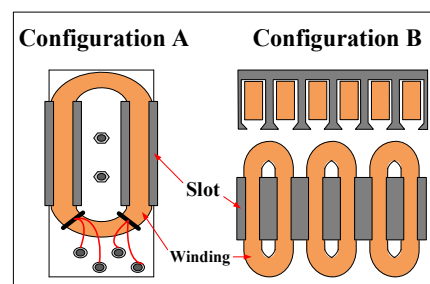

Figure 2. Common motorette configurations: "Configuration A" for a general EM and "Configuration B" for a specific EM.
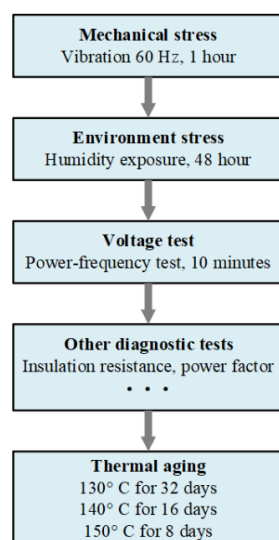

Figure 3. Accelerated thermal aging test for Class A insulation.

In addition, materials of the insulation system have different thermal expansion ratios. When they are exposed to heat, materials will expand at a different rate, leading to thermal-induced mechanical stress on the insulation. If the machine is operated under a heavy thermal cycle, then the thermal-mechanical aging should be considered [47]. A possible solution to avoid thermal-induced mechanical stress would be to remove the impregnation [48] and this method is seen in [49] with the phase separation achieved by concentrated winding topology. The absence of impregnation minimizes the occurrence of thermally induced mechanical stress, as the winding can expand freely, when heated, within their allocated volume. However, non-impregnated winding also suffers from (1) poor thermal performance (because of a lower equivalent thermal conductivity orthogonally to the conductor length); (2) poor mechanical integrity when subject to vibrations or shocks.

Unfortunately, this topic is not widely covered in literature, thus further studies are needed. In order to account for the thermal–mechanical stress, a variable temperature profile may be used instead of constant temperature during the accelerated aging test. However, there is a gap in testing the low-voltage machine as technical standards only mention the thermal cycle test [50,51] for form-wound windings. An example of a variable thermal profile aging test for low-voltage EMs could be found in [49]. Moreover, the lifetime prediction considering thermal–mechanical stress can be found in papers [47,52,53] and Ph.D. Thesis [48]. Detailed explanations will be presented later.

2.1.2. Electrical Stress

Mains-fed low-voltage EMs are mainly subjected to thermal stress and vibration [54]. However, with the advent of variable speed drive (VSD), the newly developed electrical stress caused by the repetitive, impulsive voltage challenges the winding insulation. The replacement of the BJT with IGBT and MOSFET has led to an even higher switching frequency, with the potential of several tens of kV/μs rise fronts and a 50 kHz pulse repetition frequency [26]. Moreover, there is a trend toward the use of the WBG technology in the electrical drive aimed at 100 kV/μs rise fronts and operated at a 500 kHz switching frequency [55], offering the advantage in developing an efficient, lightweight, and compact system also with the ability to operate in the high temperature [56]. The development of the switching technology offers the merits of switching loss minimization and more stable torque [26] and also pushes the electrical stress to a high level. As stated in IEC 60034-18-41, the voltage at the machine terminal can be twice as high as the inverter terminal voltage due to the impedance mismatch [22,57]. The overvoltage factor (OF) which is the ratio between machine terminal voltage and inverter terminal voltage is summarized in Figure 4 [22], depending on the cable length and inverter rise time t_r. In addition, the work extending the rise time ranging from 50 ns to 10 ns is presented in [58] to predict the effect caused by the WBG device. As a result, the voltage overshoot may reach the level to incept the PD, which is mainly responsible for insulation failure of inverter-fed low-voltage EMs [59]. Thus, the PD-free design is necessary for the low-voltage inverter-fed EMs.
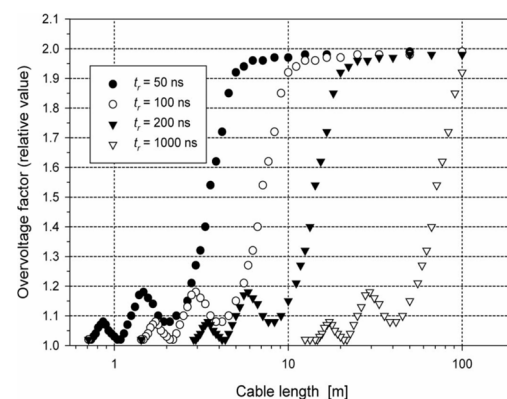

Figure 4. Overvoltage factor depending on cable length and rise time.

Apart from permanent breakdown caused by PD, several studies have investigated the aging effect of electrical stress. In [60], N. Lahoud performed the multi-stress accelerating aging test based on the design of experiments (DOE) with the result presented in Figure 5, where *M* is the average lifespan, *log(V)* and *log(T)* represent the voltage effect and temperature effect on lifetime, respectively. The findings of this study suggest that under the PD regime, both electrical stress and temperature can lead to the reduction of the lifetime. In another paper, the electrical accelerated aging test is conducted both in the absence (oil) and presence (air) of PD regime as shown in Figure 6 [61]. The evidence from this study suggests that electrical stress affects the lifetime reduction and the influence becomes much more obvious in the presence of PD. Moreover, experimental findings in [62] indicate that high frequencies, short rise times, and fast oscillating pulses shorten the lifetime. However, if no PDs occurred,

even after two years under considerably high electrical and thermal stress, no breakdown was observed. Based on these findings, treating the partial discharge inception voltage (PDIV) as the threshold for the electrical aging is reasonable, and thermal or thermal–mechanical stress would be the dominant aging factor if no PD occurs. This assumption is widely adopted in past papers [41,45,63–65].
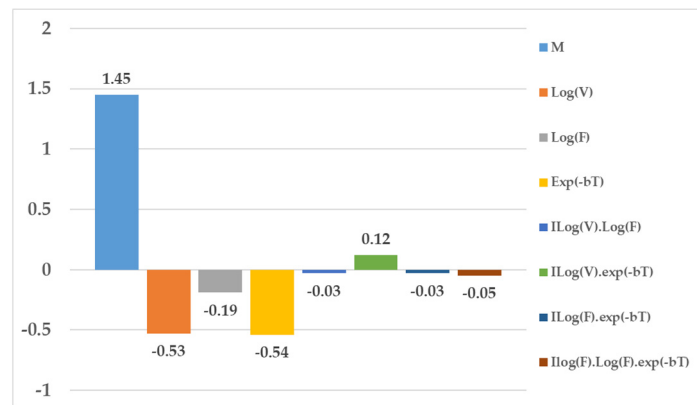

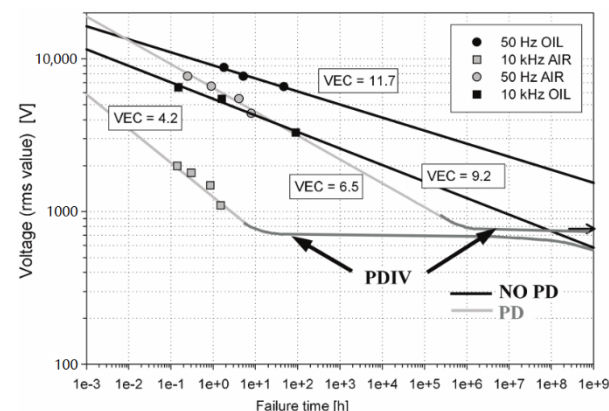**Figure 5.** Influence factors of the lifetime using DOE.

Figure 6. Electrical aging in the presence (air) and absence (oil) of PD.

2.1.3. Mechanical Stress

The power frequency currents will lead to a magnetic force oscillating at twice the power frequency. If the coils in the slot are loose, then vibration is induced and the insulation is mechanically stressed [28]. Moreover, the rotor can affect the insulation, e.g., rotor unbalance [3,66]. The mechanical stress can also come from external factors such as the vibration of a whole system which is common in mobile applications. There is no well-accepted model which can describe the aging caused by mechanical stress. Alternatively, the vibration is treated as a secondary effect factor during the main degradation process, e.g., thermal aging. As shown in Figure 3, a vibration exposure for 1 hour is adopted during the thermal aging test [31]. Moreover, the system-level vibration can be considered during the test [45] by adopting a vehicle vibration profile referring to the ISO standard [67].

2.1.4. Ambient Stress

Stresses stemming from contamination, high humidity, aggressive chemicals are categorized as environmental or ambient stress [28]. The single factor will not cause aging but the combination with other stresses may lead to aging. Thus, the ambient stress is commonly treated as "factors of influence" and according to IEC standard [31], the test samples should be exposed to the humidity environment to take into account the ambient stress.

In addition, the ambient conditions (e.g., pressure) can also impact the partial discharge phenomenon. A detailed analysis is introduced in Section 3.

2.2. The Feasible Lifetime Models

There is no doubt that a multi-stress lifetime model is always needed to accurately predict the lifetime. However, due to the complexity of distinguishing and quantifying the aging contribution caused by the simultaneous action of two or more aging factors (i.e., coupled, or combined aging effect), the single stress lifetime model is preferred. In other words, the winding is never damaged by the single aging factor but is often possible to determine which aging factor has the biggest effect [68]. Moreover, there is no generally accepted multi-stress lifetime model which could be used for reliability evaluation. The assumption of predominant aging factor is common in literature [7,69,70] and standard [27] and the feasibility has been proved by subsequent experimental results presented in technical publications [71]. As mentioned previously, a sub-cycle is applied during the accelerated aging test to account for the secondary effect (e.g., humidity and vibration).

If the machine is assumed to be PD-free and there is no heavy thermal cycle, then the thermal degradation is the dominant aging stress. Currently, the most recognized lifetime model describing thermal degradation is the one proposed by Dakin in 1948 [72] based on the Arrhenius equation, where the insulation degradation process is treated as a chemical process and the thermal lifetime depends on the activation energy and reaction rate of the particular degradation reaction. The lifetime L (in unit measure of time) under operating temperature θ calculated by Dakin's equation is expressed as:

$$L(\theta) = a \cdot \exp(b/\theta) \tag{1}$$

where a and b are parameters depending on the material properties [73]. Due to the limited wear-out data of electrical machines, these parameters are commonly derived from the accelerated aging test. The adoption of Dakin's equation can be seen in the thermal qualification standards [30,31] and published papers [45,46,49,74–93]. However, most of the papers simply apply Dakin's equation by assuming the thermal stress as the dominated aging factor without any preconditions (e.g., PD-free), which would lead to the inaccuracy of prediction. For example, if the PD occurs during the operation, the insulation will be aged very soon due to the electrical stress or even fail permanently. In addition, the lifetime model parameters (i.e., a and b) used in some papers are provided by Brancato in [75]. These data are based on an accelerated aging test on 62 Navy motor insulation systems and 31 industrial-type motor insulation systems following IEEE standards. However, the author believes the lifetime model parameters should be derived based on the costumed motorette corresponding to machine design which would account for different slot fill factor, insulation selection, and other factors related to machine design which could affect the lifetime. In conclusion, Dakin's equation is a feasible lifetime model for POF, but it should be adopted with cautions.

For transportation applications, a variable load cycle is often the case which leads to a variable temperature profile. However, Dakin's equation is applicable for a single temperature. Simply using the average value of the variable temperature profile to predict the lifetime may lead the inaccurate prediction [74]. Alternatively, the cycle counting method (e.g., rain flow-counting algorithm) could transfer the thermal cycle into mean temperature [94]. Moreover, instead of using average temperature, the method in [94] which combines the cumulative damage law [95] with Arrhenius law will give a more accurate estimation. For every infinitesimal interval dt, the temperature can be seen as constant and thus the Arrhenius equation can be applied. The fraction loss of life dLF for each time interval is:

$$dLF = \frac{dt}{L[\theta_i(t)]} \tag{2}$$

Then the loss of life LF_{cycle} for each cycle Δt_{cycle} can be derived by the simple integration:

$$LF_{cycle} = \int_0^{\Delta t_{cycle}} dLF = \int_0^{\Delta t_{cycle}} \frac{dt}{L[\theta_i(t)]} \tag{3}$$

By adopting Equation (3), the thermal lifetime under variable load can be estimated more accurately.

Moreover, as mentioned in Section 2, the repetitive temperature change may lead to thermal–mechanical fatigue. If the machine is undergoing a heavy thermal cycle, then the mechanical stress cannot be neglected [47]. A possible method would be taking the mechanical effect through the strain-life model for low cycle fatigue [48] and stress-life (S-N) model for high cycle fatigue [48,53]. The strain-life model is used [96] to describe the relationship between the plastic strain and the total number of cycles till fatigue. While stress-life model describes the relationship between the maximum stress of the cyclic elastic deformation S_{max} and the required cycles to the failure N, assuming that the cyclic mechanical stress is sinusoidal. A typical tension-fatigue curve of polyamide-imide (PAI) resin is shown in Figure 7. Once the fatigue stress is known, then the lifetime due to the thermal-mechanical stress can be obtained.
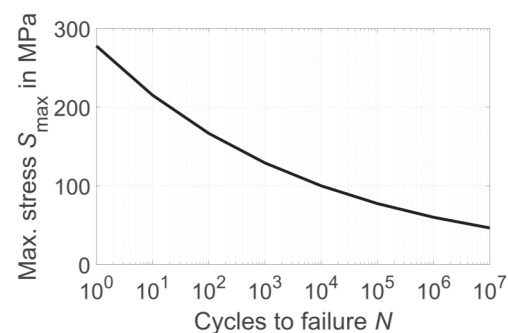

Figure 7. Tension fatigue curve of PAL 7130 [48].

Alternatively, a multi-stress thermal-mechanical lifetime is used in [47] as a combination of Dakin's Equation accounting for thermal aging and an inverse power law accounting for mechanical aging:

$$L_{T-M} = L_T L_M G \tag{4}$$

Being L_{T-M} the lifetime under thermal–mechanical stress, L_T and L_M are the single thermal stress life and mechanical stress life respectively with G being the correlation factor. Moreover, Griffo et al. [52] used the Miner's rule combined with the counting method to evaluate the induced mechanical effect while the Arrhenius Equation is used for thermal aging. A look-up table is built based on the experiment results for estimating the lifetime caused by thermal cycle stress at different temperature swings and peak temperatures. Moreover, as stated in [97], when there is no available or accurate lifetime model, a new model can be developed using a series of statistically designed experiments. An example of multi-stress lifetime model derivation based on DOE can be found in [60]. Although the author focuses on thermal and electrical stress modeling, it could be a good reference for lifetime development considering thermal–mechanical stress under a heavy thermal cycle.

2.3. The Feasibility of Adopting POF for Inverter-Fed Low-Voltage EMs

POF is a new topic on the EM application and only a few papers can be found on this topic [90,98,99]. The main barriers which impede the application of this method in the past are summarized as follow:

- The lack of fully understanding the physics of insulation degradation due to the complex operating and environmental conditions and interaction effect of multiple stress;
- The limited wear-out data of EMs compared with power electronics (PE) components.

However, based on the past study on insulation, a simple way to adopt POF in EM design is possible; refer to Dakin's Equation, the only input parameter would be the temperature. Thus, it is desirable to transfer the operating conditions into a temperature profile. Typically, thermal performance is evaluated through lumped parameter thermal network (LPTN) [100,101], finite element method (FEM), and computational fluid dynamic (CFD) [102]. According to the papers [45,46,49,74–93] estimating the thermal lifetime using the Arrhenius Equation, it is easily found that the LPTN is the most common approach [49,77,79,80,82,83,93], comparing with limited paper using FEM [89]. One possible reason could be that the LPTN is the most user-friendly solution for a fast and low-computation time-consuming thermal analysis [102]. Moreover, the influence of thermal aging on the thermal properties of EMs is investigated in [103,104] which can be easily integrated into the lifetime prediction process through LPTN.

Then it is possible to evaluate the lifetime under different inputs of the POF model (i.e., environment conditions, operating conditions, and machine design). Papers on investigating unhealthy voltage conditions on the lifetime can be found covering voltage imbalance [77–80], voltage harmonics [77,78,80], over/under voltage [79], and voltage fluctuation [88]. The unhealthy voltage conditions transfer to temperature through an electrical and thermal model. Then the Dakin's Equation is applied to evaluate the effect of unhealthy conditions on lifetime. For EMs under transportation application, the operating conditions (e.g., driving cycle/mission profile) matters. Several papers focus on the lifetime prediction with the real driving cycle or mission profile [49,81,84,91,94,105]. The authors in [49] present a comprehensive analysis of the thermal overload effect on machine lifetime. The electromechanical actuator mission profile and LPTN are combined to derive the variable temperature profile, and the lifetime model parameters are derived through an accelerated aging test with a test sample thermally exposed to the previously obtained temperature profile. Then, the lifetime under this thermal overload profile can be estimated. Similar works can be found in [81,84]. By combining the vehicle driving cycle and the lifetime model, the authors reveal that the machine can have a longer lifetime under the actual driving cycle than expected, i.e., 20,000 h lifetime, which means the oversizing of the machine. This problem has early been mentioned in [76]. The concept "lifetime-oriented design" is proposed in the paper, highlighting that the machine can be designed or operated higher than the rated power by evaluating the lifetime consumption. Moreover, different geometries and cooling methods may influence the thermal performance and thus the thermal lifetime, which means the machine design can also be linked with lifetime model via thermal model (e.g., LPTN). The work in [105] comparing the two cooling method under a typical driving cycle and the result reveals a better solution in terms of lifetime.

Based on the discussion above, it is possible to conclude a simplified lifetime prediction process taking the thermal stress as the dominated aging factor as shown in Figure 8 and it is easy to further take thermal–mechanical stress into account by modifying this process. Starting from the primary machine design which meets the performance requirement (e.g., power, torque), the thermal model is built based on the machine geometry, cooling method, and insulation selection. The derived model will take the mission profile as the input to calculate the corresponding temperature profile. The motorette will be built specifically based on machine design and then it will be subjected to the thermal accelerated aging test following the technical standard for lifetime model derivation. The aging temperature and aging time will depend on the thermal class of the selected insulation material. Environmental conditions like humidity and vibration will also be taken into account during the aging test. Finally, the lifetime will be estimated by taking the temperature profile as the input of the lifetime model.
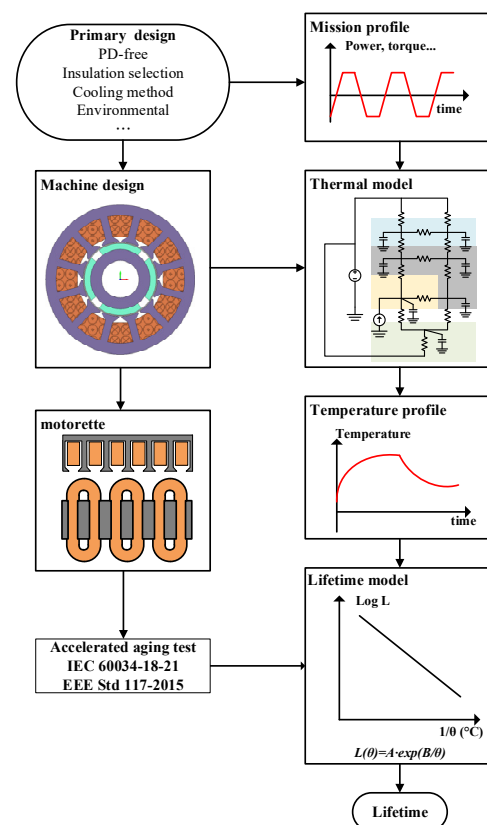
Figure 8. Lifetime prediction of low-voltage inverter-fed EMs using the POF approach.

The applicability of POF discussed above is based on the assumption of PD-free operation. Hence, the winding insulation lifetime estimation via Dakin's Equation will deliver accurate results only in absence of PD, i.e., the EM fulfills the PD-free design requirement. Thus, the next section will mainly focus on the design of PD-free EMs.

3. On the Design of PD-Free EMs

A PD is an electric discharge that only partially bridges the insulation between electric conductors and is commonly seen as the discharges in gases and the vicinity of solid/gas-insulating interfaces for low-voltage EMs [106]. According to the previous work, the premature failure of inverter-fed low-voltage EMs is due to the PD occurring in the inter-turns insulation [12]. The overshoot voltage at the motor terminal can be twice as high as the inverter terminal voltage due to the mismatch between impedance and this overshoot can reach levels at which PD is triggered in the air gap between adjacent wires. The PDs erode the insulation and consequently lead to an inter-turns breakdown. Until now, there is still not a full understanding between the PD phenomenon and insulation design, especially with the application of WBG technology. Thus, stronger insulation (e.g., oversize the insulation, use double insulation, increase the insulation grade, etc.,) is commonly applied to guarantee PD-free operation. However, this strategy will compromise the EM performance (i.e., power density, fill factor), which goes against the aim of ROD. Hence, this section aims at investigating on PD phenomenon and how to adopt the findings to design PD-free machines, paying close attention to the turn/turn insulation since it is the weakest subsystem and the occurrence of PD in turn/turn is the cause of premature failure of stator windings. The section starts with the voltage transient modeling and partial discharge modeling. These analytical methods enable machine designers to primarily evaluate the PD risk during the design stage. According to the IEC standard [22], an empirical factor which is called the enhancement factor (EF) is commonly adopted to account for the effect of influence factors on partial discharge inception voltage (PDIV) for safe operation. To move toward the ROD, the EF should be replaced with a more accurate value by understanding
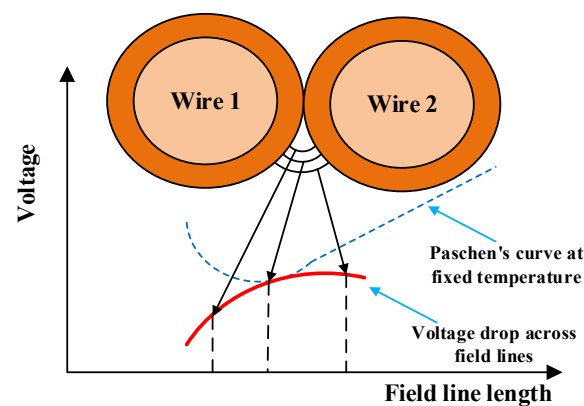
the physics of partial discharge through experimental exploration. Thus, the past work focusing on the experimental investigation of the PDIV is reviewed. Finally, as a summary of the work mentioned above, the strategy of designing PD-free EMs is highlighted.

3.1. Modelling of Voltage Transient

As stated in the IEC standard [22], the inter-turns voltage V_{t-t} can be derived by:

$$V_{t-t} = V_{DC} \cdot OF \cdot 0.7 \cdot K(t_r) \tag{5}$$

V_{DC} being the DC link voltage, $K(t_r)$ is a function of the rise time and approaches one only for a very short rise time (<50 ns); *OF* has been mentioned before as shown in Figure 4, and a winding factor of 0.7 is adopted accounting for voltage distribution [58] and may be useful when the experiment and simulation are missing. In addition to the adoption of empirical factors, the high frequency (HF) model considering machine parameters can be used to predict both the EM terminal voltage [107–115] and turn/turn voltage [107,108,114,116–119]. An example could be found in [108] as shown in Figure 9. A system-level model combining inverter, cable, and the machine is used to simulate the voltage at the machine terminal and a stator winding model is accounted for the turn/turn voltage distribution. These models can potentially build the relationship between the machine parameters and PD risk which is helpful to establish the PD-free design strategy.

Figure 9. HF model for voltage transient prediction [108].

3.2. Modelling of Partial Discharge

The breakdown voltage can be modeled by either Paschen's law [59,65,120–130] or streamer inception criterion [54,131–134]. Paschen's law is an equation that gives the breakdown voltage, that is, the voltage necessary to start a discharge or electric arc, between two electrodes in a gas as a function of pressure and gap length [135]:

$$E = \frac{U}{d} = \frac{B \cdot P}{\ln\left(\frac{A \cdot P \cdot d}{\ln(1+1/\gamma)}\right)} \tag{6}$$

E being the applied electric field, U the breakdown voltage, P the pressure, d the gap distance, and γ the Townsend's secondary emission coefficient, A and B are the coefficients that depend on the considered gas and temperature. A schematic illustrating the derivation of PDIV using Paschen's law is shown in Figure 10. The voltage level, which Paschen's curve and the voltage drop across field lines contact at a single point, is the estimated value of PDIV.

Figure 10. Computation of the inter-turn PDIV through Paschen's law.

However, the author in [54] argues that Paschen's law can be only applied to the uniform fields under quasi-static conditions and another partial discharge modeling approach called streamer inception criterion should be applied [54]. The streamer inception law starts from the well-known critical avalanche criterion [136]:

$$\int_0^{x_{cr}} \overline{\alpha}[E(x)]dx \geq K_{cr} \tag{7}$$

E(x) being the field distribution along the streamer path and K_{cr} the logarithm of a critical number of electrons, $\overline{a}$ the effective ionization coefficient, x the spatial coordinate along the streamer path, and x_{cr} is the distance at which E is equal to the critical value E_{cr}. By applying the Equation (7) to spherical voids in insulating materials, the breakdown field can be derived as [133]:

$$E_{inc} = (E_1/p)_{cr} p\left[1 + B/(pd)^n\right]/f \tag{8}$$

where *(E₁/p)cr*, *B*, and *n* are the ionization parameters for the gas, *p* is the pressure in the void, *d* is the void diameter, and *f* is the dimensionless field enhancement factor. The adoption of Equation (8) in estimating PDIV in EMs can be found in [131,132,134]. Another approach of PDIV estimation using streamer inception criterion can be found in [54]. A series of simulations are conducted using FEM to obtain the desired K_{cr} and then the breakdown filed.

In addition to the analytical approach, the PD-free criterion in [134,137] is derived by summarizing the experiment result under several test conditions into an empirical Equation and this Equation is used to check the design in other conditions.

3.3. Experiment-Based Studies on PD

According to the IEC standard [22], for a safety design (i.e., PD-free design), the inter-turns PDIV should be higher than the expected turn-to-turn voltage derived by Equation (5) multiplied by an enhancement factor (EF):

$$PDIV_{t-t} > V_{t-t} \cdot EF \tag{9}$$

The EF accounts for the temperature and the aging effect on PDIV, and the fact that PD extinction occurs at a voltage lower than PDIV (the PD extinction voltage (PDEV)). Moreover, there are some factors (e.g., humidity, pressure, inverter characteristics) that can also impact the PDIV but are not accounted for in the EF. To pursue high-performance EMs, understanding the physics of partial discharge is necessary instead of adopting the empirical enhancement factor. Many works dedicate to investigate the influence factors on PDIV or RPDIV of turn/turn insulation [54,62,120,123,138–153] through experiments. A typical experiment setup for PDIV investigation is presented in Figure 11. Twisted pairs are the preferred test sample since turn/turn is the weakest subsystem subjected to the

partial discharge [62,154] and twisted pairs are the easiest sample to evaluate the inter-turn PD phenomenon according to the IEC standard [22]. An environment chamber is used to study the influence of ambient conditions (i.e., temperature, pressure, and humidity). In terms of source, a high-voltage pulse generator is adopted instead of a sinusoidal source to follow the real operational conditions of inverter-fed EMs. For PD detection, an optical approach using photomultiplier has an advantage over others in terms of noise immunity, especially under the very high switching frequency of voltage.
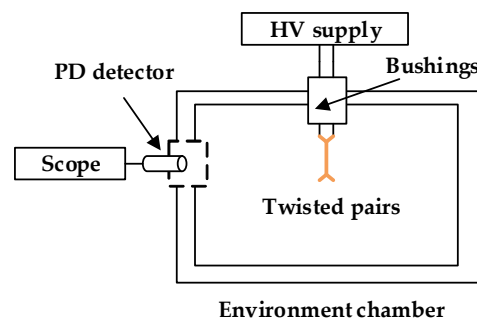
Figure 11. A typical PDIV investigation experiment setup.

3.3.1. Effect of Ambient Conditions

Both temperature [54,62,120,123,140–142,155] and pressure [120,138,142–144,152,153] have great impact on the PDIV. In general, the PDIV decreases with the increase of temperature and the reduction of pressure. When the pressure goes below a certain threshold, PDIV increases with the further decrease of pressure as shown in Figure 12 [138].
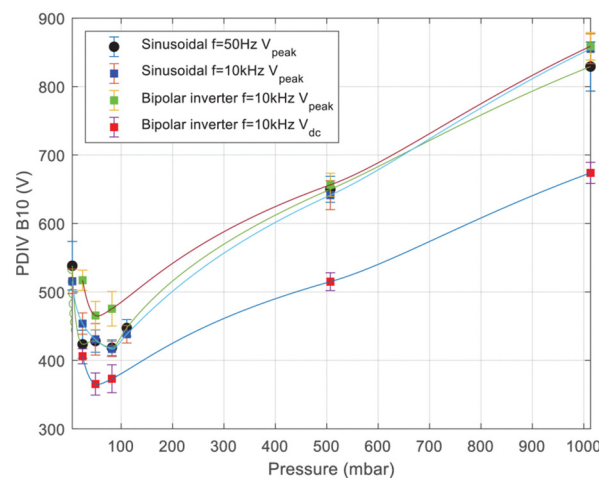

Figure 12. PDIV under different pressure [138].

This phenomenon is expected. Referring to Paschen's law, for a fixed distance between two turns, there would be a certain pressure threshold that represents the lowest PDIV and the pressure level below or above this point will have a higher PDIV. According to the PD modeling approach mentioned above, either Paschen's law or streamer inception criterion takes the pressure effect into account. To further account for the thermal effect, Paschen's law is modified in [123,126,142,144] to take the temperature as a parameter of the model. Moreover, the equivalent pressure is used combined with streamer inception criterion to take both temperature and pressure effect into account in [54]. Besides the analytical model, the curve-fit approach is adopted in [120] to describe the relationship between PDIV and temperature based on the experimental findings. The same method can be found in [134,152] where both temperature and pressure are considered. Humidity can also influence the PDIV, and the investigation on twisted pairs can be found both under ac voltage [121,140,145,156] and surge voltage [140]. No general tendency can be concluded

since the effect of humidity may both depend on temperature [156] and voltage type [140]. An attempt trying to explain the humidity effect on PDIV is given in [121] based on the relationship between space charge and PDIV presented in [157].

3.3.2. Effect of Thermal Aging

The thermal aging effects on PDIV has been studied in [35,139,142,152] and all the experimental results indicate the decrease of PDIV with time of aging. The authors of [152] argue that for MEA application, thermal aging is not as severe as industry application, and the aging enhancement factor is modified as:

$$EF_{Aging} = \max(1, 1.1 \times T_S / T_C) \tag{10}$$

T_s and T_c being the service and class temperature, respectively. A similar consideration is proposed in [120], where the authors suggest that the thermal aging effect can be neglected for MEA applications.

The work attempting to model the thermal aging effect on PDIV can be seen in [142], claiming that the main change of PDIV is due to the relative permittivity change of the insulation coating. By taking the relative permittivity change with thermal degradation into the PDIV modeling, the analysis result shows a good match with the experimental results.

3.3.3. Investigation on PDEV

The investigation on PDEV can be found in [120,155,158–160]. The higher voltage level and longer rise time lead to a high PDEV [158–160] and higher switching frequency and temperature may lead to lower PDEV [155]. A safety factor of 1.25 is recommended in the IEC standard [22] and the experimental findings reported in [120] tend to agree on this value, for round enameled wire specimen. However, the authors compared the measured PDEV and PDEV calculated by safety factor at different temperatures as shown in Figure 13, indicating the single factor of 1.25 for all operating points is unsuitable [155].
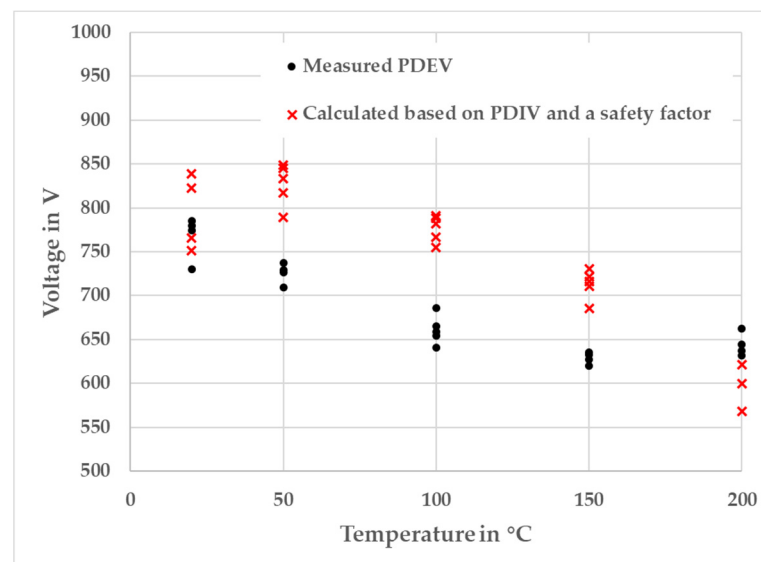

Figure 13. Measured and calculated PDEV based on the safety factor at different temperature [155].

Moreover, according to the experiment result as shown in Figure 14 [155], PDEV decreases with the increase of frequency, while the PDIV almost does not change. These findings highlight the requirement of a deep understanding of PDEV to better and safely design the PD-free machine.
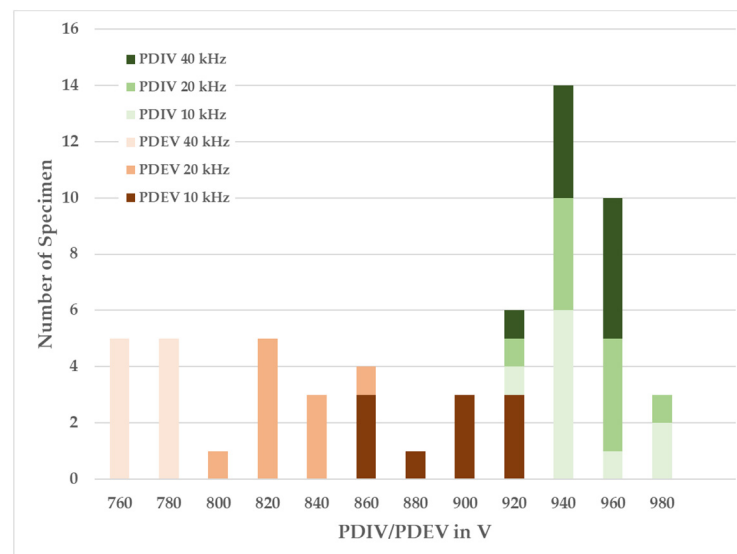
Figure 14. PDIV and PDEV of ten twisted pair specimen at different switching frequencies [155].

3.3.4. Effect of Insulation Thickness and Conductor Diameter

Refer to Equation (6), the breakdown electrical field depends on the distance which means conductor diameters and insulation thickness will impact PDIV although these effects are not mentioned in the standard. Published papers can be found focusing on insulation grade [54,62,123,152] and conductor diameter [54,62,123] effect on PDIV. An empirical model considering grade, diameter, and pressure is proposed to model the PDIV [137] and a tool is developed in [129] aiming at designing a PD-free EM considering grade and diameter. Moreover, the outcome in [54] turns out to be a recommendation chart of PDIV at the worst case as shown in Figure 15, for different conductor diameters and insulation thickness. This could be a useful reference for EM designers during the wire and insulation selection.
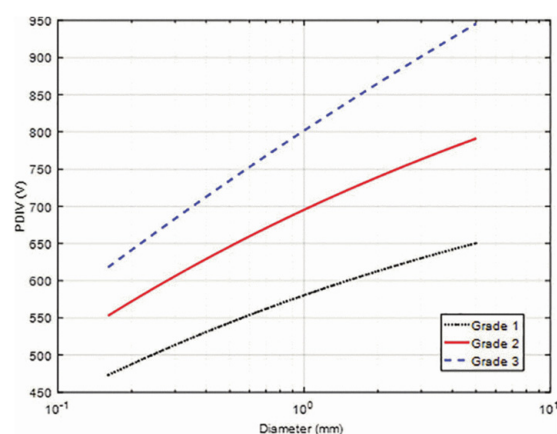

Figure 15. Worst case curves at ambient temperature (relative permittivity is equal to 4) [54].

3.3.5. Effect of Surge Voltage Characteristic

The impulsive voltage caused by the inverter may influence PDIV although the effect is also not highlighted in the standards. Typically, a surge voltage is characterized by rise time, repetition frequency, and duty cycle and a couple of work studying the influence on PDIV can be found for each topic: rise time [62,130,138,148], frequency [138,143–145,147–149,153], and duty cycle [147,148]. To account for the potential insulation challenge caused by the WBG device, some papers have conducted the investigation based on the WBG device. The rise time can be down to 7 ns [138] with a slew rate of 140 kV/μs and the switching frequency can reach 600 kHz [159]. Unfortunately, there is no general conclusion that can be drawn based

on these papers since the test voltage conditions are quite different and the PDIV may be affected by the combination of rise time, frequency, and duty cycle. In general, rise time will have a quite large impact on PDIV while the frequency and duty cycle have less influence. A volume–time theory-based simulation model is attempted to account for the rise time effect in [130], and a good match can be found at the rise time of 80 ns. Moreover, a try on PDIV modeling combining pressure and frequency can be found in [144] although the result does not show a good match.

As stated in IEC 60034-18-41 [22], the insulation system can be both qualified using sinusoidal voltage or impulsive voltage. However, the study in [138,140,150,151,157,161,162] indicates that there could be a difference between PDIV measured by sinusoidal voltage and surge voltage, and the level of the inverter can have a strong influence [150,151]. Moreover, the polarity of the square wave may also impact PDIV [59,157,162]. Thus, the EM is recommended to be tested under surge voltage [163] with test conditions similar to the real operating conditions.

3.4. Design of PD-Free EMs

The work mentioned above helps to understand the physics of partial discharge and the PD-free design methodology can be found in published papers [54,65,120,128,134,137,152] and Ph.D. thesis [106]. Based on the findings above, it is possible to conclude a general PD-free design methodology as shown in Figure 16.
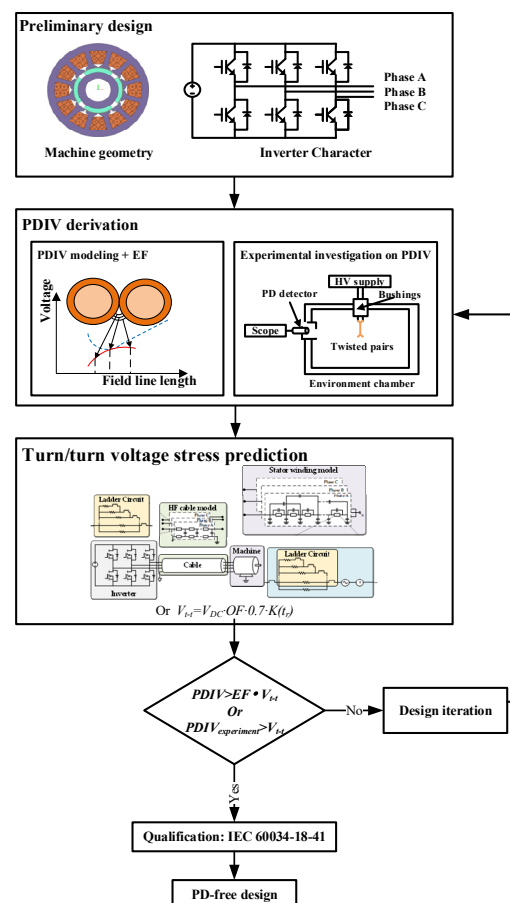

Figure 16. A summarization of PD-free design process.

Starting from machine design and inverter characteristics, PDIV is first estimated either using an analytical model approach combined with enhancement factor or experimental derivation. Note that the experimental investigation mainly focuses on the effect of different conditions (e.g., pressure, temperature, switching frequency, etc.,) on PDIV which is empirically assumed in EF. Then the turn/turn voltage stress can be modeled either by

high-frequency circuit model or empirical factor as shown in Equation (5). Then the PD risk can be evaluated by Equation (9) or the below Equation:

$$PDIV_{experiment} > V_{t-t} \tag{11}$$

where $PDIV_{experimental}$ represents the PDIV derived by experiment taking the influence factors (e.g., ambient, aging) on PDIV into account; thus, there is no need to correlate $PDIV_{experimental}$ by EF. The design iteration is needed to obtain the best performance while avoiding the PD risk. It is important to note that the process in Figure 16 is the PD-risk evaluation at the design stage while the final market-ready product should be developed before qualifying according to the IEC standard.

4. Moving towards a Reliability-Oriented Design Approach of EMs

There are two possible solutions to move toward a ROD approach of EMs. First, Researchers should keep the continuous investigation on the insulation degradation from physical and chemical aspects for developing a more accurate lifetime model. Alternatively, a simple but recognized lifetime model will be used by carefully adopting a series of assumptions and pre-condition to predict as reliable as the real result. This paper mainly focuses on enabling the second approach through reviewing the past papers and tries to fill the gap between insulation degradation and machine design. Fortunately, for inverter-fed low-voltage EMs which are free of PD, treating thermal or thermal-mechanical stress as the dominated aging factor is acceptable. Combining the work in Sections 3 and 4, it is possible to give a more comprehensive ROD process. The EM should be first designed to be PD-free considering the converter's parameters (e.g., switching frequency, DC link voltage), then the lifetime can be estimated through the Dakin's Equation or thermal-mechanical model. Many rounds of design iterations are needed to meet the reliability requirement while pursuing better performance at the same time. An expected achievement through the ROD can be seen in Figure 17. Through understanding the physics of failure, the over-engineering issue can be avoided to some extent which means lower grade insulation (i.e., thinner insulation) or higher current density may be adopted to obtain a higher power density while keeping the reliability requirement at the same time. It is worth mentioning that the ROD is a design methodology during the design stage. However, the final prototype should be qualified by technical standards before becoming a market-ready product. Thus, there is no need to doubt whether the real life of the EM is equal to estimation by the so-called lifetime model or not, which is both hard and impossible. However, continuous investigation on the dielectric area allows EM designers to assess the reliability during the design stage instead of empirical design and over-engineer factors adoption. The main effort should be put into making the lifetime prediction as reliable as possible.
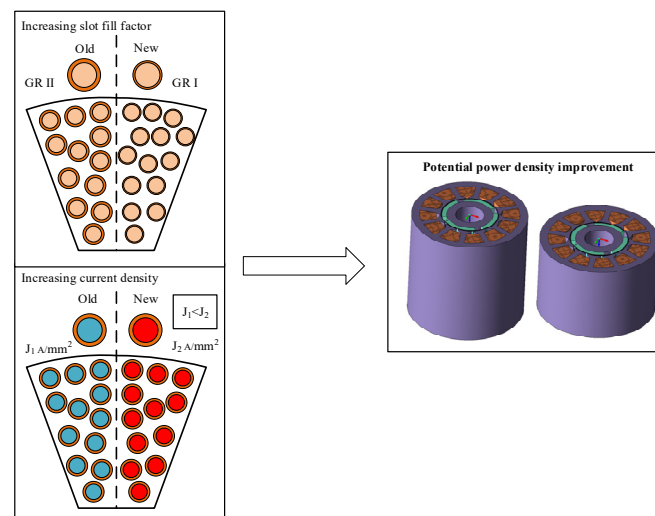
Figure 17. Potential performance improvement by adopting ROD.

5. Conclusions

High-performance and reliable EMs are more and more demanded by transportation electrification applications. Hence, the PoF methodology, which considers both operational and environmental conditions as input and based on the lifetime model predicts the EM reliability level, should be employed since the early EM design stage (i.e., reliability-oriented design) in order to avoid the EM over-engineering. By applying the PoF approach to the EM design, satisfactory reliability figures can be reached without compromising the EM performance. The paper provides an overview regarding the major investigations in the area of dielectric materials typically adopted for EMs manufacturing and their implication on EM design. The main aim of this work is to pave the way for enabling the reliability-oriented design for inverter-fed low-voltage EMs, which are the most suitable candidates for transportation of electrification applications.

The review begins with a general background on the stresses (i.e., TEAM stresses) faced by inverter-fed low-voltage EMs and then focuses on PD-free design and lifetime prediction. Finally, a comprehensive reliability-oriented design process is presented as a potential solution to achieve a reliable and high-performance EM. Indeed, assuming an EM designed to be PD-free, the thermal stress becomes the dominant aging factor and Dakin's Equation can be used to accurately predict the lifetime. From a practical point of view, accelerated aging tests are commonly performed to derive the lifetime model. In particular, an adequate number of test samples (i.e., specimens), which are built based on the specific EM design and materials, are thermally aged at three different temperatures according to IEC or IEEE standards. The experiment-based lifetime model (i.e., outcome of the POF methodology) will be then used at the EM design process to preliminary assess the EM reliability in order to meet the demanded reliability figures. By adopting such a strategy, it is expected to improve the dielectric material exploitation through an appropriate design of insulation, while ensuring the key EM performance indicators (e.g., power density).

The EM reliability-oriented design discussed in this paper represents a feasible and convenient approach to be employed by EM designers in order to find out the best trade-off between reliability and performance according to the application under study.

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